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Control Technology Overview Report CFC-11 Emissions from Flexible Polyurethane Foam Manufacturing

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CONTROL TECHNOLOGY OVERVIEW REPORT:
CFC-11 EMISSIONS FROM FLEXIBLE POLYURETHANE FOAM MANUFACTURING

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Halohydrocarbons		Flexible Foams	07C
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ABSTRACT

The report gives results of an engineering evaluation of technical options to reduce chlorofluorocarbon (CFC) emissions from flexible slabstock and molded polyurethane foam manufacturing plants. Among the technical options examined were recovery and recycle of CFC-11, alternative chemicals and processes, and substitute products. Two possible emission control methods were studied in detail: substitution of methylene chloride as the auxiliary foam blowing agent and carbon adsorption/recycle of exhausted CFC-11 vapors. Promising near-term control options identified for slabstock production were methylene chloride substitution for CFC-11, and establishment of a minimum foam density to reduce the amount of auxiliary blowing agent used. For molded polyurethane foam production, use of chemical systems which eliminate the need for auxiliary blowing agents appeared to be a near-term option. Possible longer-term options included carbon adsorption with CFC-11 recovery, development of chemical systems requiring little or no auxiliary blowing agents for slabstock production, and commercialization of new alternative blowing agents. Each longer-term option has in common a need for additional information to adequately define the optimal implementation strategy.

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SECTION 1
PROJECT DESCRIPTION

BACKGROUND

Over the past decade, depletion of stratospheric ozone through the action of halocarbons has been the subject of extensive study, and wide debate. This phenomenon involves a complicated set of interactions that are driven by ultraviolet radiation and occur within the upper atmosphere. Not only are the interactions extremely complex, but direct observations of them are difficult. Current evidence suggests that man-made halocarbons could contribute to depletion of the stratospheric ozone layer, although many scientific uncertainties remain.

An important aspect of the ozone depletion problem is the lag time between the emission of halocarbons into the environment and their ultimate arrival in the upper atmosphere. Therefore, any effects of current emissions would not be manifested until several years later. Cumulative emissions of halocarbons to date have created a reservoir from which halocarbons can continue to diffuse into the upper atmosphere for several years, even if emissions immediately halted.

A family of fully-halogenated halocarbons known as chlorofluorocarbons (CFC) are the primary suspects in the ozone depletion theory. Since they are stable, CFCs have a long life in the atmosphere and are not readily decomposed by the levels of ultraviolet radiation present in the lower atmosphere. Once a CFC molecule has been transported into the stratosphere, it can be acted upon by the ultraviolet radiation, which releases chlorine atoms that can act as reactants in the breakdown of ozone to diatomic oxygen. Such depletion of the protective layer of stratospheric ozone would result in increased ultraviolet radiation to earth which may cause adverse effects including increases in melanoma cancer, reduced crop yields, photochemical degradation of plastics, and changes in the global climate.

CFCs are widely used in several industries including flexible polyurethane foam manufacturing. In that industry, CFC-11 (fluorotrichloromethane) is used as a physical blowing agent to reduce foam density and increase softness. Another key role of the CFC-11 blowing agent is to dissipate heat generated by the polyurethane formation reactions to control foam temperature during formation and curing. As an auxiliary blowing agent (carbon dioxide gas from the foam reactions is the primary blowing agent), CFC-11 increases the volume of gas liberated within the polymer matrix during foam rise, therefore increasing foam porosity and decreasing foam density. CFC-11 is used in this manner for both flexible slabstock and molded foam. The amount of blowing agent in a given formulation depends on the density and softness specifications of the product.

Emissions of CFC-11 blowing agent from the flexible foam manufacturing process are characterized as being prompt, i.e., the gas is released during, or soon after, foam formation. Therefore, in this industry the quantity of CFC-11 emitted essentially equals the amount consumed. Data compiled by the Chemical Manufacturers Association (CMA) indicate that, since CFC-11 release is prompt, flexible foam production accounts for about 30 percent of current CFC-11 accumulation in the atmosphere (1).

Chlorofluorocarbon use in the flexible foam industry is increasing in the United States and worldwide. According to CMA estimates, the annual CFC-11 consumption of the flexible polyurethane foam industry in the United States was 14.8 thousand metric tons (32.6 million pounds) in 1985. Of this total, 11.5 and 3.3 thousand metric tons (25.3 and 7.3 million pounds), respectively, were used in the manufacture of flexible polyurethane slabstock foam and molded foam parts (2). Thus, in 1985, the flexible foam industry accounted for 20 percent of the total U.S. consumption of CFC-11.

PROJECT OBJECTIVES

The primary objective of this project was to evaluate technical options to reduce emissions of CFC-11 from flexible foam plants. In this study, the following areas were given priority: recovery and recycle of CFC-11, alternative chemicals and processes, and substitute products. An in-depth evaluation of the factors involved in these priority areas was performed. These factors include estimated emissions of CFC-11 from various foam production processes and end-uses; and the availability of control for these sources. For all control technologies, engineering and economic aspects have been examined, as well as barriers to control implementation. The relative effectiveness of each potential control technique was examined. A profile of the flexible foam industry including a roster of active firms, description of process technology, and projected market growth, has also been prepared.

In this overview study, the depth of technical evaluation was limited, in some cases, by the information available on each technology. However, two possible emission control methods have been extensively studied: substitution of methylene chloride as the auxiliary blowing agent and carbon adsorption/recycle of exhausted CFC-11 vapors. For each of these, sufficient data was developed for a detailed evaluation which addressed key technical factors, safety, economics, current status, and control cost effectiveness. The effectiveness of control consists of both the degree to which emissions can be curtailed, and the estimated costs per unit of averted CFC-11 emission. For these two options, control effectiveness was evaluated using cost estimates prepared for implementation of controls at typical slabstock foam production facilities.

An important component of this study was to summarize recent innovations in foam technology which have the potential to reduce or eliminate CFC-11 use. Most of these advances are currently in the developmental or early commercial stages, so in some cases limited information was available to predict control costs on a commercial scale. The specific areas in which data are lacking are identified as part of these evaluations. From this information, it may be possible to identify the most advantageous areas for future research and development.

SECTION 2

SUMMARY OF RESULTS

In the production of flexible polyurethane foam, CFC-11 (fluorotrichloromethane) is used as a physical blowing agent to reduce the foam density and increase softness. Another important function of CFC-11 is to dissipate some of the reaction exotherm generated by formation of polyurethane. CFC-11 is applied in this manner for both flexible slabstock and molded foam, with the portion of blowing agent in a given formulation dependent on the density and softness specifications of the product.

According to 1985 estimates, 11.5 and 3.3 thousand metric tons (25.3 and 7.3 million pounds) of CFC-11 were used in the production of slabstock and molded foam, respectively, in the United States (2). The total consumption by the flexible foam industry accounts for about 20 percent of the total United States usage of CFC-11. Moreover, emissions of the CFC-11 blowing agent occur during, or soon after, foam formation so emissions from this source closely match consumption. There are slightly over 100 facilities currently producing flexible slabstock foam, and about 40 molded foam plants (3,4). The largest end-uses for polyurethane flexible foam are the automotive and furniture industries, accounting for more than 50 percent of total foam output (2).

This study has evaluated a number of technical options which could reduce the emission of CFC-11 from flexible foam plants. Candidate technologies were examined with respect to engineering, safety, and economic factors. The availability and current status of these technologies were also evaluated. Relevant barriers to implementation were identified, and if appropriate, a reasonable time frame was proposed for control implementation.

COMPARISON OF AVAILABLE TECHNICAL OPTIONS

Emission control techniques evaluated in this study included carbon adsorption, substitute blowing agents, alternative foam processes, and substitute products. The applicability of a given control to flexible foam production was assessed, as well as the availability and current status of the technology. And, important barriers that may impede implementation were identified. Comparisons among these options can be made on the basis of technical factors which determine the possible reduction in emission, and economic factors that affect the control costs. Table 2-1 presents a summation of all of these key factors for all major technologies examined in this study. Comparisons presented in Table 2-1, such as for control cost ranges, are based on the current flexible foam manufacturing practices, with no CFC controls.

Control methods in the area of capture and destruction or recycle techniques include carbon adsorption of CFC-11, thermal or catalytic incineration, liquid absorption, and direct vapor condensation. Findings from pilot tests have shown that carbon adsorption may be feasible for CFC-11 control. However, a number of technical issues have not been satisfactorily resolved, including fouling of the carbon bed by isocyanate residue, quality of recycled CFC, and disposal of used carbon and steam condensate. The remaining control methods in this category suffer from either high cost or a preponderance of negative technical factors, which would prevent their application for flexible foam plants. As a result, these less favorable add-on controls have not been attempted at flexible foam facilities.

The cost effectiveness of carbon adsorption/recycle was found to be highly variable, depending on the CFC-11 market price, recovery efficiency, facility size, and required capital investment. It is felt that this control method is more applicable to slabstock facilities than molded foam plants, due to potentially more efficient capture of released blowing agent from the slabstock process. High capital costs are a substantial barrier to implementation. This is because the competitive nature of the foam business makes it

TABLE 2-1. SUMMARY OF CFC-11 EMISSIONS CONTROL OPTIONS IN FLEXIBLE FOAM MANUFACTURE

I. Add-on Control/Recycle

Factor	Carbon Adsorp. with recycle	Incineration, Thermal or Catalytic	Liquid Absorption	Vapor Condensation
Percent emission reduction	40 - 60	10 - 60	10 - 40	0 - 30
Control cost effectivness ($/mt)	$700-$5800/mt[a] offers recovery credit of up to $1,300/mt[b].	Extremely costly; no recovery credit.	Expensive, offers recovery credit.	Extremely costly; offers recovery credit.
Control Applicability	Good for slabstock, poor for molded.	Poor, CFCs are difficult to incinerate.	Fair, requires specialized solvent.	Poor
Availability and Status	Fair, pilot-trials at foam plants inconclusive.	Fair, seldom used for high volume streams, no trials for foam plant.	Fair, seldom used for high-volume streams, no trials for foam plants.	Poor, not generally applicable to dilute streams.
Barriers to Implementation	High capital expense; ventilation modification needed; waste disposal costs.	Excessive operating cost; very high capital costs.	Solvent emissions, high operating cost; possible technical problems.	Excessive operating costs; high capital costs with low recovery.

(Continued)

[a] Specific control costs based on examples in Section 5.
[b] Recovery credit based on 1985 CFC-11 price estimates.

TABLE 2-1 (Continued)

II. Alternative Blowing Agents

Factor	Methylene Chloride ($MeCl_2$) substitution	Alternate CFCs Having Ozone Depleting Potential Lower than CFC-11
Percent Emissions Reduction	Up to 75% over all slabstock grades; generally, low density, soft grades can only be made with CFC-11.	50-100% depending on compatibility with all foam formulations.
Control cost effectiveness ($/mt)	$1400/mt[b] credit to $1900/mt[b] net cost depending on scrap rate and ventilation modif. Up to $3500/mt[b] cost if carbon adsorption required.	Blowing agent cost may increase up to 5 times, product cost increases in proportion to softness (more blowing agent needed).
Control applicability	Good for slabstock, very poor for molded foam.	Good, if substitute chemical has correct properties.
Availability and Status	Excellent, is currently widely used.	Fair, possible candidate CFC's are not yet commercially available.
Barriers to Implementation	Regulatory uncertanties in regard to $MeCl_2$ toxicity; reformulation and conversion costs; more difficult process and quality control; additional ventilation-heating and cooling costs.	Potentially higher cost; some chemicals toxic or flammable; development time uncertain.

(Continued)

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[b] Specific control costs based on examples in Section 6.

TABLE 2-1 (Continued)

III. Equipment Modification and Work Practices

Factor	Max-Foam® Process (Unifoam AG)	Vertifoam® Process (Hyman International)	Leak detection and repair
Percent emission reduction	Up to 20% claimed by licensee, no data available. Experience indicates that reduction is low.	0% directly, but add-on control eased by equipment arrangement.	2 %[c]
Control cost effectiveness ($/mt)	Unknown	Unknown	Poor, because of low emission reduction; Equip. leaks $4000/mt[c] Storage $80,000/mt[c].
Control Applicability	Good for slabstock lines, delivers flat top bunstock.	Fair, applicable to new installations only.	Fair, low emission reductions, can be applied to all foam plants.
Availability and Status	Excellent, majority of foamers use this process.	Good, one U.S. supplier, four new installations in U.S.	Very good, employs conventional maintenance.
Barriers to Implementation	Requires capital expense to retrotit older plants; licensing fee.	New installations only; special building requirements; licensing fee.	Added maintenance costs

(Continued)

[c] As estimated for methylene chloride emissions.

TABLE 2-1 (Continued)

IV. Alternative Chemicals and Processes

Factor	HR Water Blown Molded Foam Based on TDI or MDI	Water-blown slabstock, modified polyols	Formic Acid "AB" Process (Innochem, S.A.)
Percent emission reduction	Estimated at 80-100% of consumption for molded foams.	30-90%, depends on developments in formulations, foam quality and processability.	50 - 100, depending on applicability to particular foam grade.
Control cost effectiveness ($/mt)	Unknown	Unknown	Uncertain, developer claims operating cost saving.
Control applicability	Can currently be used for most molded foam parts.	Most firmness grades should be possible at higher density.	Developers claim most foam grades can be produced, range is probably limited.
Availability and Status	Available systems are starting to replace CFC-blown systems.	Preliminary research stage, commercial systems not yet available.	Tested in Europe, no commercial use reported.
Barriers to Implementation	Product quality must satisfy consumers, reject rate high for lowest density parts.	Slightly increased chemical costs; lack of commercial experience; licensing fee.	Requires corrosive hazardous acid; CO released; lack of commercial experience; licensing fee.

(Continued)

TABLE 2-1 (Continued)

V. Alternate Products

Factor	Higher minimum density CFC-11-blown foam	Non-flexible foam cushioning materials (e.g. cotton batting)
Percent emission reduction	Estimated at 30 - 50%	5 - 15%, depending on ability to substitute currently available materials.
Control cost effectivenes ($/mt)	Unknown, sensitive to chemical costs versus foam market price.	Unknown, additional development costs are undefined.
Control applicability	Good, would eliminate molded and slabstock low-density foams which use the most CFC-11.	Poor, many technologies are outdated, alternatives not developed for high-volume end-uses.
Availability and Status	Excellent, no change in current technology.	Poor, large change in end-use product designs are necessary.
Barriers to Implemenatation	Higher chemical costs; higher product costs; loss of lightweight foam materials; need to consider end-use costs and consumer preferences.	More costly cushioning materials; higher resource and energy consumption; large end-use and foam industry displacements; may not satisfy consumer preferences.

difficult for producers to commit large sums of capital. It would also be difficult to offset annualized operating costs through the recovery credit for recycled CFC-11. Another potential problem is the control of secondary pollutant streams from large-scale use of carbon adsorption for CFC-11 recovery, such as treatment of fouled carbon and steam condensate, which has yet to be evaluated.

A few substitute auxiliary blowing agents have been suggested as replacements for CFC-11. Methylene chloride is currently used as the auxiliary blowing agent for about half of all slabstock flexible foam. A longer-term possibility is alternative CFC-type blowing agents having less ozone depletion potential, but these chemicals are not currently in commercial production.

Although methylene chloride has a higher boiling point than CFC-11, advances in catalyst chemistry have facilitated its increased use as an auxiliary blowing agent for flexible slabstock. However, given current technology, methylene chloride is not applicable to molded foam production. There are two main concerns with expanded use of methylene chloride; possible toxic effects of work-place exposure and the inability to produce as wide a range of foam properties as with CFC-11. There is also some uncertainty about future regulation of methylene chloride emissions, which might greatly increase the cost of this substitute blowing agent as a means of controlling CFC-11 emissions.

The short-term availability of methylene chloride conversion as a CFC-11 control measure is excellent, since a majority of slabstock producers now employ this technology. It is estimated that as much as 75 percent of all flexible slabstock foam could be produced using this alternative blowing agent. Full conversion to methylene chloride generally requires some expenditure for foam reformulation and plant modification, such as improved ventilation in foam curing areas. These costs, and subjective preferences of some producers and customers, are significant impediments to maximum substitution. Operating costs at some plants could be higher, because methylene chloride formulations require more sensitive control, which can cause higher scrap rates. Also, space heating and/or cooling costs may increase due to higher plant ventilation rates.

Alternative CFCs having ozone depletion potentials lower than CFC-11 are a promising long-term control method. Three possible candidates have been identified: CFC-123, CFC-133a, and CFC-141b. Of these, CFC-123 appears to be both reasonably safe and technically feasible, however, CFC-123 production costs are claimed to be higher than CFC-11. Also, there is no commercial scale production of CFC-123 in the United States, due to impediments in developing a commercial process, and lack of an assured market.

Since the amount of auxiliary blowing agent required for a given flexible foam is established by the formulation chemistry, only minor reductions in emissions are possible by equipment modification or work practices alone. Two types of slabstock pouring equipment have been introduced that could offer some control benefit, primarily by increasing the blowing efficiency or simplifying collection of vapors emitted from the process. One such configuration, which has been adopted by most foam producers, is trough-feeding, or the Max-Foam® process. In this arrangement, feed liquid is introduced at the bottom of a trough at the leading edge of the slabstock conveyor, and this ensures complete entrainment and more efficient utilization of the volatile blowing agent.

A novel concept in slabstock production, which was first commercialized in 1982, is called the Vertifoam® process. This process employs a vertical chamber to convey the rising foam mass upward, and individual buns are cut off at the top of the chamber. By confining CFC-11 emissions over a relatively smaller area, the vertical conveyor could simplify CFC vapor capture and recovery using an add-on device such as a carbon adsorber. However, accessibility of control equipment to exhaust stream may be a deterrent.

Quantitative data on emission reduction for either of these equipment configurations could not be developed from available information. Both of these technologies require a licensing arrangement, which would slightly increase operating costs.

Work practices such as improved leak detection and repair programs could deliver small emission reductions at moderate direct cost. A recent Radian study has shown that storage and equipment leakage accounts for about two percent of methylene chloride releases from foam plants (5). Therefore, modified work practices would have little effect on the CFC emissions from these facilities. Also, the cost effectiveness of these measures is poor, in terms of cost per unit CFC emission controlled, because of the small emission reduction.

There have been several recent innovations in the area of polyurethane molded foam chemical systems which could ultimately reduce or eliminate the need for auxiliary blowing agents. In general, these newer systems utilize established HR auxiliary blowing agents (high-resilience) technology, but permit foam production without CFC-11. These systems employ either conventional TDI reagents, or a class of isocyanates referred to as MDI (methylene diphenyl isocyanate) compounds, and families of more reactive polyols. It is not currently possible to economically achieve U.S. auto seat specifications using water-blown MDI-based formulations. But, TDI-based water-blown systems are available that can produce all currently used molded foam grades. Only slightly increased raw material costs are anticipated for these systems.

New chemical systems have also been introduced which would permit production of softer, water-blown slabstock foam. These systems employ more reactive, and generally more expensive, polymeric or "soft" polyols which produce a higher density, high softness foam. Specific control cost data are not available for these developmental chemical systems. To date, there are no commercial applications of advanced water-blown polyurethane slabstock.

Another slabstock process which could reduce the need for CFC-11 blowing agent has been developed in Belgium, and is currently licensed by Innochem S.A. in Switzerland. This process, which is claimed to be applicable to a range of slabstock grades and some molded foam components, substitutes formic acid for some of the water in the formulation, and the subsequent reactions release twice the volume of blowing gas as with conventional chemistry. The additional gas is carbon monoxide, which is a recognized toxic gas; so extra monitoring and safety precautions are necessary with this process. And, handling of the concentrated formic acid requires special ventilation precautions and materials of construction. There have been no reported full-scale applications; but some testing of this process has been carried out in Europe.

Alternate cushioning products, such as cotton or polyester batting have a relatively poor potential to greatly reduce CFC-11 emissions. This is mainly due to the lack of comparably priced substitutes having the same durability and properties as polyurethane foam. While technically feasible alternative cushioning products might be developed, it is doubtful that the performance of flexible polyurethane could be matched in most applications. Specially engineered cushioning, using more dense and/or firm foam, or porous plastics supplemented by springs, internal voids, etc., would be somewhat more expensive to produce, using current technology. In addition, the relatively low weight per unit volume of polyurethane foam is an important advantage in many uses. Secondary market effects, such as increased resource and energy use and loss of competitiveness in end-use products, also provide disincentives for abandoning polyurethane foam cushioning.

One product modification that could significantly reduce CFC-11 emissions is development of minimum density specifications for polyurethane foam in different end uses. Since the largest amount of auxiliary blowing agent is required for the lowest density foam, elimination of these low density materials could reduce total CFC-11 usage by as much as 40 to 50 percent. The resulting foam product would usually be more durable, and in some applications would have a longer service life. Implementation of this measure would cause foam producers to purchase more raw material costs per unit of foam produced, and these costs would ultimately be passed to the consumer. Additional end-use fabrication costs, and other secondary market effects, are an important consideration for this control. A more detailed market study to better define the overall economic effects of higher-density foam, and to specify optimal density standards, is an appropriate next step in this area.

As a means of reducing CFC-11 use, the minimum foam density concept may have an additional benefit. At higher densities, the economics of foam manufacture incresingly favor the use of methylene chloride blowing agent. Therefore, if low density foams were eliminated, there could be a synergistic enhancement in emission reduction, as producers voluntarily shift more production to methylene chloride.

PROMISING CFC-11 CONTROL OPTIONS FOR FLEXIBLE FOAM PLANTS

On the basis of the evaluations undertaken in this study, it is possible to group the more promising control options into short-term and longer-term measures. Table 2-2 displays the proposed grouping along with less promising options for control of CFC-11 emissions from flexible foam plants. The criteria used in this ranking include the overall emission reduction potential, control cost, the impact on the foam industry and end-use markets, and ease of implementation.

Based on these evaluations, substitution with methylene chloride, establishment of a minimum foam density, leak detection and repair programs, and use of water-blown molded foam systems can be categorized as possible short-term emission control measures. Increased use of product substitutes, such as natural or synthetic fiberfill, might also reduce the use of CFC-11 to produce lower-density foam.

Possible longer-term options include carbon adsorption with CFC-11 recovery, development of water-blown foam chemistry for slabstock, and commercialization of alternative CFC blowing agents. Each of the longer-term approaches have in common a need for additional information in order to adequately define the optimal implementation strategy.

It is most important to recognize that economic pressures in the flexible foam industry, if driven by the cost of CFC-11 emission compliance, could alter the current situation. This in turn could cause rapid advances in, and commercialization of, more environmentally sound control technologies.

Another possible consequence may be reduction in overall foam production, since producers may elect to not implement costly or technically complex controls.

TABLE 2-2. RANKING OF CONTROL ALTERNATIVES FOR CFC-11 IN FLEXIBLE FOAM MANUFACTURE

Option (Section Discussed)		Advantages/Disadvantages	Immediate Information Needs
Possible Short-Term Options			
Methylene Chloride Substitution (6)	Adv:	Good reduction potential, accepted technology.	In-plant emissions study, safety assessment.
	Dis:	Moderate conversion costs, toxicity uncertainties; potential emission regulations, can not be used with molded foam.	
Minimum Foam Density (9)	Adv:	Good reduction potential, no development necessary	Market analysis to assess impact.
	Dis:	Costlier end-products possible, since raw materials costs would increase per unit foam volume.	
Low-density cushioning substitutes (e.g., natural synthetic fiberfill) (9)	Adv:	Currently available, competitive cost with slabstock foam.	Market analysis to assess impact.
	Dis:	Reduced cushioning performance and durability.	
HR Water-blown molded foam using TDI or MDI (8).	Adv:	Minimal conversion costs, most foam grades can be produced.	Evaluation of ultimate market penetration for currently availalbe systems.
	Dis:	Slightly higher raw material costs, difficult to produce lowest density grades.	
Leak Detection and Repair (7)	Adv:	Simple, conventional maintenance practices	Plan for implementation and enforcement
	Dis:	Low CFC emission reduction potential	

(Continued)

TABLE 2-2 (Continued)

Option (Section Discussed)	Advantages/Disadvantages	Immediate Information Needs
Possible Longer-Term Options		
Carbon Adsorption With CFC-11 Recovery (5)	Adv: Recycles emissions, recovery credit Dis: High capital expense, waste disposal problems, more complex plant design and operation.	Pilot tests to evaluate commercial potential.
Water-Blown Slab (e.g., "Soft" Polyols) (8)	Adv: Eliminates or lowers CFC use, permits good foam qualities. Dis: Uncertain economics, applicable to limited range of foam grades, commercial potential uncertain.	Commercial demonstration and economic evaluation.
Formic Acid (AB) Process (8)	Adv: Eliminates CFC use, applicable to range of foam grades. Dis: Carbon monoxide emissions, handling of conc. formic acid, need for corrosion-resistant materials, no commercial demonstrations.	Commercial demonstration and evaluation.
Non-Commercial Alternative CFC Compounds (6)	Adv: Potentially unchanged blowing agent performance, minimal change in foam technology. Dis: More costly, not yet available, toxicity and flammability need to be assessed.	Detailed evaluation of potential commercialzation, complete toxicity testing.

(Continued)

TABLE 2-2 (Continued)

Option (Section Discussed)	Advantages/Disadvantages	Immediate Information Needs
Less Promising Options		
Thermal Destruction (5)	Dis: Energy intensive, high capital costs, corrosive combustion products.	
Liquid Absorption (5)	Dis: High capital costs, emissions of sorbent liquid, contamination of blowing agent by sorbent.	
Vapor Condensation (5)	Dis: Large refrigeration requirement, high capital costs.	
Alternate foams, natural fiberfill with springs, other high density cushioning substitutes.	Dis: Potentially higher costs to consumers, reduction in product quality, substitutes not feasible for certain uses, secondary environmental and energy consumption effects.	

SECTION 3

FLEXIBLE FOAM INDUSTRY AND CFC EMISSION PROFILE

OVERVIEW OF FLEXIBLE FOAM MANUFACTURE

In the manufacture of flexible polyurethane foams, chlorofluorocarbons are used as auxiliary blowing agents to assist in giving the foam its cellular structure. These compounds volatilize during the foaming process to create open cells within the urethane polymer matrix. Such materials are considered auxiliary blowing agents since carbon dioxide (CO_2), the primary blowing agent, is released in relatively larger volumes as a by-product of the water/isocyanate reaction. For many foam grades having densities greater than about 32 kg/m^3 (2 lb/ft^3) CO_2 is the only blowing agent required. Currently, the chlorofluorocarbon used virtually exclusively to produce flexible foams is trichlorofluoromethane (Cl_3FC), which is referred to in industry literature as CFC-11, R-11, or F-11.

Flexible polyurethane foam is produced in two forms, slabstock and molded, and serves as cushioning material in a wide variety of end uses. Flexible polyurethane slabstock foams are used predominantly in furniture, bedding, and carpet underlay. Molded foams are used primarily as seat components in the automotive industry, and for some specialized uses in the furniture industry. While CFC-11 is used exclusively in molded foam production, methylene chloride, a chlorocarbon (CH_2Cl_2), is a widely accepted alternative currently used as an auxiliary blowing agent in about half of the total U.S. production of flexible slabstock foam production.

The auxiliary blowing agent in foam manufacture is best described as a chemically inert participant in the mechanism of foam production. One key reaction is the exothermic reaction of toluene diisocyanate (TDI) with a polyol. This reaction forms the urethane monomers, which can then polymerize. Water also reacts with the isocyanate to form an amine and carbon dioxide gas. The CO_2 gas liberated by the water reaction acts as the primary blowing agent, but the amount released is not sufficient to produce the softness, flexibility, and low density desired in many foam products. A volatile, auxiliary blowing agent is thus required. Also, since timing of blowing agent release in the foaming process is crucial, specialized catalysts are used to control CO_2 release and urethane polymerization. Other additives such as flame retardants and stabilizers complete a typical flexible foam formulation and impart specific properties to the foam. A more thorough discussion of flexible polyurethane foam chemistry and technology is provided in Section 4 of this report.

Two key physical properties of flexible foam are density and firmness. The former refers to the weight of foam per unit volume. Firmness is defined as the ability of the foam to resist compressive deformation. A standard measure of firmness adopted by the flexible foam industry is the Indentation Load Deflection (ILD) index. The ILD index refers to a standard measure of force required to achieve a set percentage, for example 25 percent, of foam compression. Although the ILD is an indirect measurement, it is a key foam specification. The softest foams have an ILD of 10 or less, while the most firm commercial foams have ILD values greater than 40.

Foam density and firmness properties are generally controlled by the relative amounts of water and auxiliary blowing agent in the feed mixture. These variables are inter-related, and other foam ingredients can also exert an influence. To illustrate, higher water levels tend to reduce foam density by increasing the volume of CO_2 produced, and to increase firmness by contributing to urea cross-linking in the polymer matrix. Also, as more water is included in the formulation, more exothermic heat of reaction is generated, which may raise foam temperatures to undesirable levels. Use of an auxiliary blowing agent, such as CFC-11, permits lower densities to be achieved without raising the water content. In this way, greater foam softness is also obtained. Volatilization of the auxiliary blowing agent also helps dissipate the exotherm generated by the water/isocyanate reaction. Additional components, such as surfactants and catalysts, can affect foam properties by modifying open cell size and polymer gelation.

Chlorofluorocarbon emissions from flexible foam production are prompt, meaning that nearly all the blowing agent is released from the open cell structure during, or soon after, foam formation. This is in contrast to rigid foams, which hold the blowing agent in a closed cell matrix for an extended period of time after manufacture. The prompt nature of CFC-11 emissions is an advantage with respect to emission control in flexible foam production.

Slabstock Production

Flexible foam slabstock is produced on a foam line, which is essentially a conveyor belt that can be over 60 meters long. By far the most common production method is referred to as the "one-shot" process. The raw foam product is in the form of a "bun", or loaf. In recent years about 70 to 80 percent of United States and world flexible foam output is in the form of slabstock, which can be produced in a multitude of firmness and density grades. As an example, Figure 3-1 shows a product mix for a typical slabstock plant on the basis of foam firmness as measured by Indentation Load Deflection (ILD). This distribution is reasonably representative of both United States and European production.

In commercial continuous-slab production by the one-shot process, the reactants are pumped by accurate metering pumps from storage tanks, through heat exchangers, to dispensing nozzles at one end of the foam line. The mixed reactants pour onto a continuously moving belt or web of release paper. Foam is formed as the reactions take place, and the material expands until it fills the foam tunnel and reaches its final density. There is a variety of foam equipment, each with proprietary features that can affect permissible foam formulations, bun geometry, and process control. Two types of feed dispensing

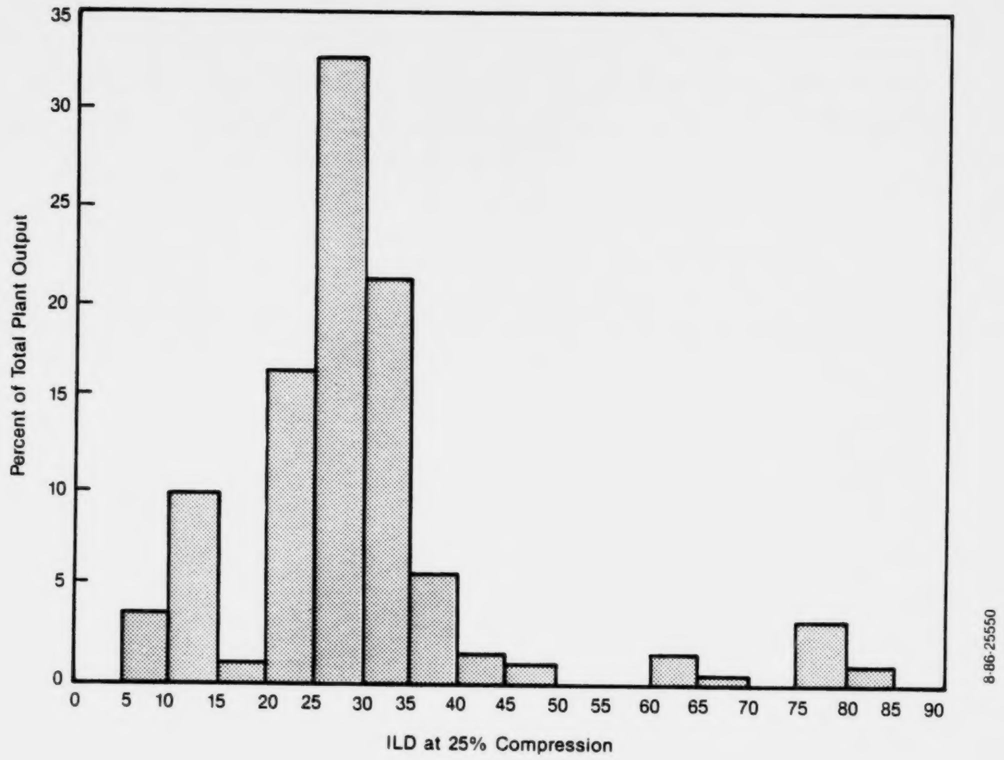


Figure 3-1. Product mix of a typical flexible urethane slabstock plant.

Source: (35)

arrangements are currently in use. Older systems use a single traversing head, which lays the unreacted foam ingredients back and forth across the conveyor. Most installations favor trough dispensing, in which the feed is injected into a trough at the leading edge of the conveyor. The reacting foam materials spill over the trough and flow down the tunnel conveyor. The advantage of this process is a more rectangular bun with less trimming waste.

Most of the foam formation reactions occur within the initial portion of the foam line, in a foam tunnel. The foam tunnel consists of an inclined conveyor belt constrained on the sides by plastic or metal curtains. The foam slab formed may be 1 to 2 meters wide and 1 to 1.5 meters high, depending on foam density and throughput. Most slabstock process conveyors range from 15 to 40 meters in total length, and travel at speeds of 3.5 to 6 meters/min. The foam bun exits the tunnel as formed slabstock, ready to be sawed off into slabs 3 to 15 meters long. Finished product foam shapes, such as thin pads or furniture cushions, are cut from these large slabs.

Typically, the slab reaches its maximum height within about four minutes to ten minutes, depending on the formulation. Additional time on the conveyor is required to allow completion of the polymerization reactions, so that the foam will solidify. It is critical to product quality and consistency that the foaming reactions are closely timed, and come to completion at nearly the same moment. Therefore, process operation and control often requires subtle formulation adjustments.

Prior to the advent of the ozone depletion theory linking chlorofluorocarbon emissions with destruction of the ozone layer, CFC-11 was the auxiliary blowing agent used exclusively in flexible slabstock foam manufacture. In recent years, due to environmental impetus to reduce CFC emissions and to economic factors, CFC-11 and methylene chloride (CH_2Cl_2) now hold an almost equal share in this auxiliary blowing agent market (2,3,4,5). CFC-11 has been found to possess more favorable properties with respect to volatility, inertness, and nonflammability. However, methylene chloride has been adopted for certain slabstock grades, mainly because of its lower cost. Although CFC-11 is used extensively in "super soft" and/or lower density foam grades, mixtures of CFC-11, methylene chloride, and other volatile hydrocarbons are available that may be suitable even for some low density foams products (6,7,8).

Molded Flexible Polyurethane Foam Production

When molded polyurethane foams first came into widespread use in the 1960's, the "hot molding" process was used almost exclusively. In recent years, the high resiliency (HR) cold molding process has become the favored alternative to the hot molding process (9,10). As of 1983, over 90% of molded automotive foam was produced using HR formulations (11). In molded foam manufacture, metal or fiberglass foam molds are mounted on a carousel, and moved sequentially to various operations. A typical sequence might include mold preheat, raw materials addition, mold closure, curing, mold opening, demolding, and mold cleaning. After exiting a pre-heating oven, the molds are filled with a precisely measured quantity of pre-mixed raw material from a dispensing head. After an adequate cure time, the molds are opened and the foam product demolded. Most molded foam products are then crushed by rollers, which ruptures any remaining closed cells and gives the foam open-cell characteristics.

Foams made using HR formulations have a wide range of load-bearing properties, and these formulations can generally be made fire retardant more easily (12). The HR foam process is distinguished from the hot molding process by chemical formulations which permit molded components to be made without heat curing. More highly reactive polyol systems are used, which permit complete cure without external heating. By adjusting the raw material formulation, it is possible to produce a foam using 25 percent less CFC per pound than was required for components made by the older hot molding process (13,14).

For molded polyurethane foams, CFC-11 remains the dominant auxiliary blowing agent. This is because the most likely substitute, methylene chloride, can impart undesirable characteristics to the molded parts due to its solvent properties. Surface blemishes, non-uniform density, and a "sticky" surface are common problems prohibiting methylene chloride use. Also, the use of CFC-11 varies because cushioning design criteria in the auto industry are different between manufacturers and for the various interior components. In Europe, for example, molded foam products for automobiles tend to be of higher density and firmness. Water-blown foam systems, which require no auxiliary blowing agent, are commercially available for molded foam production, and their application is becoming more widespread, especially in the auto industry (14,15).

FLEXIBLE FOAM INDUSTRY PROFILE

Flexible Foam Production and Uses

Annual output of molded and slabstock flexible polyurethane foam in the United States has exceeded 400 thousand metric tons since the mid-seventies. The highest volume end-uses for polyurethane flexible foams are in the furniture and automotive industries. Today, almost all new furniture and bedding cushioning is flexible polyurethane foam. Automobile seat bottoms and backs are almost exclusively produced using molded flexible foam, which currently accounts for 150 thousand metric tons of foam in the United States (2). Carpet underlay is another major end-use of flexible foam and is made from flexible foams typically consisting of 43 percent virgin foam rebonded with 57 percent recycled scrap (16,17). A small percentage of flexible polyurethane foam is used in the textile manufacturing industry. The packaging market is about equally divided between molded shapes and die-cut flexible foam used to package goods such as electronic products, instruments, and pharmaceuticals.

One important observation with respect to control of CFC emissions in the flexible foam industry is the high degree of product specialization which has evolved. Current foam technology permits a foamer to closely control the density, resiliency, and softness of the finished product. One key process variable in achieving this range of properties is the amount and type of auxiliary blowing agent included in the foam formulation. Should restrictions on blowing agent use reduce the range of versatility, foam demand may be reduced significantly.

Trends in the density and firmness properties of foams used for individual end-markets also affects the use of auxiliary blowing agents. Recent patterns in the furniture and automotive industries offer good examples of this. From 1979 to 1983, the average density of flexible foam consumed by the residential furniture market declined from about 26 kg/m^3 (1.65 lb/ft^3) to less than 21 kg/m^3 (1.3 $lb./ft^3$) due to retail price pressures (19). Since total furniture foam consumption increased during this period, this probably indicates greater use of auxiliary blowing agents. In contrast, the average density of foams used for automobile cushions and non-residential furniture has increased in recent years. Production of these materials would thus be expected to consume decreasing amounts of auxiliary blowing agents.

In general, trends in polyurethane foam consumption have followed economic growth patterns. The output of the slabstock industry is closely related to the output of the furniture, bedding, and carpet industries. Similarly, trends in production of molded foams usually follow the output level of the automobile industry. Because of this, most sources expect future demand for flexible foams to grow at approximately the same rate as the GNP; but many other factors, such as housing starts, exert a more direct influence.

Estimates of future increases in total flexible polyurethane foam production have ranged as high as 3 to 8 percent (18); however, since the foam market is relatively mature, most industry sources cite growth rates in the 1 to 3 percent range (19). Recent projections have placed foam demand in the year 2000 at about 50 percent above 1985 consumption. However, uncertainty in GNP extrapolations result in a range of error in this projected use of 20 to 25 percent (2). Actual market data compiled by the Society of Plastics Industries has shown an overall decline in flexible polyurethane production of 1.9% during the period 1978-83 (20). Reasonable overall growth projections must presume differing growth rates in the foam end-use markets. For example, from 1978 to 1983, annual use in the furniture market increased by nearly 1.0

percent; packaging and textile usage grew by 2.8 percent annually; and rug underlay use increased by 4.5 percent. However, other end-use consumption declined during this period; transportation by about 7 percent, and bedding by 1.5 percent (19,20). Flexible foam production projections for the United States, shown in Table 3-1, were obtained by combining annual growth rates of 1 or 5 percent in total flexible foam consumption with historical data.

Most flexible foam facilities are located near their end-use markets, since long-distance transportation costs for the low density foam material could outweigh product value. Major market areas for slabstock foam are furniture, bedding, and carpet manufacturing centers in Southern California, the mid-Atlantic states, the Southeastern states, and most major metropolitan regions (3). Most firms producing molded polyurethane parts are located near automotive assembly plants; a majority of the facilities are located in Ohio, Indiana, Michigan, California, and the northeastern United States (4). As might be expected from the disproportionate transport costs, little or no flexible foam is imported or exported.

There is a substantial degree of vertical integration in the flexible foam industry. The largest volume producers of molded foam include automotive and furniture manufacturers; from one-third to half of automotive foam components are produced captively by the large automotive manufacturers. Many smaller-volume facilities are operated by custom molders with a small, relatively specialized client base (13,18).

Table 3-2 displays a breakdown of historic consumption of flexible polyurethane foams according to end use. As noted previously, the largest consumers are furniture and automotive products, accounting for about 35 percent and 30 percent, respectively, of United States foam output (16,16,19). Since the mid-seventies, annual United States production of slabstock foam (excluding molded foam) has been between 425 and 475 thousand metric tons, except during the economic recession in 1981-82. Use of molded foams in automobiles, the single largest end-user of these materials, has fluctuated between 130 and 180 thousand metric tons during this same period (2).

TABLE 3-1. HISTORICAL AND PROJECTED UNITED STATES FLEXIBLE FOAM PRODUCTION: 1960 - 2015

Year	Flexible Foam Production Slabstock and Molded (1000 mt/yr)	(million lbs/yr)
1960	38	(86)
1965	108	(241)
1970	276	(618)
1975	435	(974)
1980	539	(1190)
1985	603	(1330)
	Low Growth (1% annual)	High Growth (5% annual)
1990	635 (1400)	772 (1700)
2000	700 (1550)	1260 (2770)
2015	810 (1790)	2610 (5750)

Sources: (2,26,84)

TABLE 3-2. CONSUMPTION OF FLEXIBLE POLYURETHANE FOAM BY APPLICATION

	1980	1981	1982	1983	1984	1985		
	Thousand Metric Tons (millions of pounds)							
						Slabstock	Molded	Total
Furniture	193 (432)	195 (437)	192 (431)	205 (452)	210 (463)	175 (386)	40 (88)	215 (474)
Transportation	125 (275)	115 (253)	120 (264)	136 (301)	160 (352)	65 (143)	115 (253)	180 (397)
Rug Underlay	72 (161)	94 (165)	63 (141)	76 (168)	96 (211)	115 (253)	—	115 (253
Bedding	62 (139)	64 (143)	56 (125)	64 (141)	61 (134)	55 (121)	—	55 (121)
Textile	17 (38)	16 (36)	15 (34)	14 (30)	13 (28)	10 (22)	—	10 (22)
Packaging	14 (31)	16 (35)	15 (34)	17 (37)	17 (37)	10 (22)	6 (13)	16 (35)
Miscellaneous	26 (58)	18 (40)	15 (33)	13 (29)	10 (22)	4 (9)	1 (2)	5 (11)
Scrap	30 (66)	20 (44)	14 (31)	15 (33)	13 (29)	6 (13	3 (6)	9 (19)
Total	539 (1,200)	538 (1,186)	490 (1,093)	540 (1,191)	580 (1,276)	440 (969)	165 (362)	605 (1,330)

Sources: (2,16,17,19,20,21,84)

Tables 3-3 and 3-4 list the significant producers of flexible slabstock and molded foams, respectively. According to a recent U.S. industry survey (1985), about 105 facilities operated by 47 firms were involved in pouring of flexible slabstock foam or fabrication of product components (3). Of these, more than half employ methylene chloride as an auxiliary blowing agent to some extent, while relatively few foamers use only CFC-11 or methylene chloride exclusively. Usually, an auxiliary blowing agent is selected that offers the most consistent quality and lowest cost for a given foam grade using the customary formulation for that producer; however, there are a number of intangible factors influencing this choice. A more detailed discussion of blowing agent selection appears in Section 4 of this report.

In the slabstock foam industry, there is a great deal of similarity in the equipment used by large and small volume foamers; differences in facility output depend on the period of time the foam line is in operation. Most facilities, especially smaller volume producers, may only operate the foam line for a few hours per day, on average. As a result, only about one-third of the total foam production capacity is utilized; if "capacity" is defined as the total potential output of all plants operating for an 8-hour daily shift (18). Among the factors that can limit plant output are limited local market demand, warehousing constraints, and transportation costs.

There are fewer molded foam plants than slabstock facilities, since total demand for this product is lower, and economies of scale are more important. As of 1985, 39 operating molded foam plants were identified, representing 28 firms (4). A large portion of molded foam output is produced captively and is destined for a particular customer located near the plant itself.

The equipment required for molded foam plants is vastly different than for slabstock plants. At most facilities, individual molds are conveyed along an automated production line that runs through numerous processing steps. The entire line might be computer controlled in order to achieve high production

TABLE 3-3. ROSTER OF U.S. FACILITIES POURING FLEXIBLE POLYURETHANE SLABSTOCK AND/OR FABRICATING SLABSTOCK FOAM PRODUCTS AS OF 1985

Company	Facility Location	Company	Facility Location
American Foam	Miami, Florida	Foamex Products	Corry, Pennsylvania E. Providence, Rhode Island Elkhart, Indiana Milan, Tennessee Thomasville, Georgia Torrance, California
Austin Urethane	Americus, Georgia	Future Foam	Anaheim, California Council Bluffs, Iowa Middleton, Wisconsin Newton, Kansas Northglenn, Colorado Omaha, Nebraska
Burton-Dixie	Blacksburg, South Carolina	General Foam	Bridgeview, Illinois E. Rutherford, New Jersey West Hazelton, Pennsylvania Paramus, New Jersey
Consolidated Foam	Beaumont, Texas	General Foam of Minnesota	St. Paul, Minnesota
Crain Industries	Chicago,Illinois Compton, California Conover, North Carolina Elkhart, Indiana Ft. Smith, Arizona Kent, Washington Newman, Georgia San Antonio, Texas San Leandro, California	Great Western Carpet	Orange, California
Crest-Foam	Moonachie, New Jersey	GSF Corporation	Andover, Maryland
Dow	Torrance, California	Hickory Springs	Americus, Georgia Conover, North Carolina Ft. Smith, Arkansas Hickory, North Carolina Tupelo, Mississippi
E R Carpenter	Calgary, Alabama Conover, North Carolina Elkhart, Indiana Richmond, Virginia Riverside, California Russellville, Kentucky Temple, Texas Tupelo, Mississippi		

(Continued)

TABLE 3-3. ROSTER OF U.S. FACILITIES POURING FLEXIBLE POLYURETHANE SLABSTOCK AND/OR FABRICATING SLABSTOCK FOAM PRODUCTS AS OF 1985 (Continued)

Company	Facility Location	Company	Facility Location
Eastern Foam	Cookeville, Tennessee	MIP Inc.	Brenham, Texas Cold Water, Mississippi Ft. Worth, Texas Houston, Texas Tupelo, Mississippi
Easton	Easton, Pennsylvania	NC Foam	MT Airy, North Carolina
Flexible Foam Products (Ohio Decorative)	Bremen, Indiana Cairo, Illinois Chattanooga, Tennessee Spencerville, Ohio	Olin Corporation	Fogelville, Pennsylvania
Florifoam	Miami, Florida	Olympic Products (Cone Mills)	Greensboro, North Carolina Tupelo, Mississippi
Foam Fabricating	Chattanooga, Tennessee	Penn Foam	Raubsville, Pennsylvania
Foam Molding	San Antonio, Texas	Plastaner	Livonia, Michigan
Hi Life Products	Atwood, California	Prestige	Ashboro, North Carolina
Hood Industries	Leomister, Maine Wakefield, Maine	Ramco Ind.	City Industry, California Los Angeles, California
Hyman Pacific	Wilmington, Deleware	Recticel Foam	Buffalo, New York LaPorte, Indiana Morristown, Tennessee Thomasville, North Carolina
Indiana Foam Fab.	Elkhart, Indiana	Reeves Brothers	Auburn, North Carolina Cornelius, North Carolina Orlando, Florida
Lear Siegler	West Chicago, Illinois		
Leggett & Platt	High Point, North Carolina Tupelo, Mississippi		

(Continued)

TABLE 3-3. ROSTER OF U.S. FACILITIES POURING FLEXIBLE POLYURETHANE SLABSTOCK AND/OR FABRICATING SLABSTOCK FOAM PRODUCTS AS OF 1985

Company	Facility Location	Company	Facility Location
Reliance Upholstery	Gardena, California	Trinity Foam of North Carolina	High Point, North Carolina
Scotfoam	Conyers, Georgia Dallas, Texas Eddystone, Pennsylvania Fort Wayne, Indiana Mesquite, Texas San Bernadeno, California	Triumph Cushion	Carson, California
Scottdell, Inc.	Swanton, Ohio	United Foam	City of Commerce, California Hayward, California Honolulu, Hawaii Portland, Oregon
Sheller-Globe	Iowa City, Iowa Verona, Mississippi	Universal Urethanes	Houston, Texas Mansfield, Texas
Superior Products	Plantersville, Mississippi	W.T. Burnett & Co.	Baltimore, Maryland Jessup, Maryland

TABLE 3-4. ROSTER OF U.S. FACILITIES PRODUCING MOLDED POLYURETHANE FLEXIBLE FOAM COMPONENTS AS OF 1985

Company	Facility Location
Allen Industries, Inc.	Compton, California
American Seating Company	Grand Rapids, Michigan
Artco Enterprises	Thief River Falls, Minnesota
H.L. Bachford, Inc.	Troy, Michigan
Burris Industries, Inc.	Lincolnton, North Carolina
Cartex Corporation	Addison, Illinois Doylestown, Pennsylvania Far Hills, Pennsylvania
Catelli Industries, Inc.	Bohemia, New York
Chromecraft Corporation	Senatobia, Mississippi
Corbin Gentry Corporation	Somerville, Connecticut
Davidson Rubber	Americus, Georgia Athens, Tennessee
Flexible Foam	Cairo, Illinois
Ford Motor Company	Utica, Michigan
General Motors	Elyna, Ohio Dayton, Ohio
Goodyear Tire and Rubber	Logan, Ohio Luckey, Ohio
Harvey Probber, Inc.	Fall River, Massachusetts
Herman Miller, Inc.	Holland, Michigan Irvine, California Zeeland, Michigan
Hoover Universal	Adrian, Michigan Greenfield, Ohio Whitmore Lake, Michigan
Kern Foam	Sommerville, New Jersey
Lear Siegler	Wisconsin
Michigan Seat Company	Jackson, Michigan
MTD Products, Inc.	Strongsville, Ohio
Polaris Industries	Roseau, Minnesota
Reiss Industries	Waterton, Wisconsin
Sears Manufacturing Company	Davenport, Iowa
Sheller-Globe Corporation	Iowa City, Iowa Keokuk, Iowa Niles, Michigan
Tempress, Inc.	Seattle, Washington
Uniroyal	Mishawaka, Indiana
Woodbridge Corp.	Broadhead, Wisconsin

levels and extremely accurate product quality control. Because the capital commitment is large, entry into and exit from this market are relatively rare, except for smaller speciality molders.

CFC-11 Production and Consumption by the Flexible Foam Industry

Table 3-5 lists the five major U.S. producers of chlorofluorocarbons along with estimates of their total capacities (22). Approximate percentages of capacity allocated to CFC-11 production are also shown in the table (2). The allocation of capacity to individual CFC products is uncertain, since these compounds can be produced jointly or separately utilizing the same process equipment.

Recent compilations of CFC-11 production for both the United States and major world producers are available. Historic data for CFC-11 output, based on a 1984 survey by the Chemical Manufacturers Association covering the largest producer countries (United States, West Germany, Japan, Italy, Netherlands, United Kingdom, France), is shown in Table 3-6 (1). This compilation excludes the Soviet Union and East Bloc countries because recent data have not been reported, but production in these countries amounted to only three percent of total world output as of 1975. It can be observed that production of CFC-11 (and some other chlorofluorocarbons) peaked in the early 1970s. Since that time the CFC production rate in these reporting nations has declined, in part due to the United States' ban on non-essential fluorocarbon aerosol propellants, and in part to a shift to methylene chloride blowing agent by the foam industry.

In Table 3-6 the portion of CFC-11 sales through 1984 by the major world producers that can be attributed to flexible foam manufacturing activity is noted (1). The percentages of total CFC-11 use for rigid and flexible foam blowing have increased, because CFC-11 use in these categories has increased, and because use as an aerosol propellant has decreased by nearly a factor of two during the 1976-84 period. There has been an overall increase of about 50

TABLE 3-5. MAJOR U.S. PRODUCERS OF CHLOROFLUOROCARBONS

Producer and Facility Location	Annual Capacity Thous. of Metric Tons (millions of pounds)	Estimated Percent of Capacity Allocated to CFC-11
El DuPont de Nemours Antioch, California Corpus Christi, Texas Deepwater, New Jersey Louisville, Kentucky Montague, Michigan	290 (605)	24
Allied Corporation Baton Rouge, Louisiana Danville, Illinois Elizabeth, New Jersey El Segundo, California	178 (400)	23
Pennwalt Corporation Calvert City, Kentucky	54 (120)	29
Essex (Racon) Chemical Corporation Wichita, Kansas	38 (85)	13
Kaiser Aluminum & Chemical Corporation Gramercy, Louisiana	36 (80)	28
	565 (1,265)	

Sources: (2,22)

TABLE 3-6. PERCENTAGES OF TOTAL WORLD CFC-11 SALES ALLOCATED TO VARIOUS END USES: 1972 - 1984

Year	Refrig.	Rigid Foam Blowing	Flexible Foam Blowing	Aerosols	Other	Total Sales 1000 mt (million lbs.)
1972	NA	NA	NA	NA	NA	255.8 (573.1)
1974	NA	NA	NA	NA	NA	321.4 (720.1)
1976	7.9	15.3	13.2	57.4	6.2	339.8 (761.4)
1978	8.8	21.3	17.2	46.5	6.2	308.9 (692.0)
1980	10.0	29.0	18.4	36.3	6.3	289.6 (648.9)
1982	9.0	35.0	16.8	34.0	5.2	271.4 (608.2)
1984	7.7	35.4	20.3	31.2	5.4	312.3 (700.0)

NA = Not Available
Source: (1)

percent in the demand for flexible foam during this same period, as shown in Table 3-1.

In 1985, the United States accounted for approximately 22 percent of total world use of CFC-11, including the contribution from the East Bloc countries. Estimates for 1985 indicate that about 20 percent of United States CFC-11 production was used as flexible foam blowing agents with about 75 percent of that amount used for slabstock and the remainder for molded foams (2). The corresponding statistics for nations reporting to the CMA are 16.5 percent of CFC-11 production allocated to flexible foam production, with 13 and 3.5 percent attributable to slabstock and molded foams, respectively (2,23).

It should be pointed out that 18 percent of United States and 11 percent of world CFC-11 production in these most recent reports were unaccounted-for quantities with respect to usage. Work conducted by Radian concurrently with this study has identified that a large portion of this shortfall for 1985-86 may be attributable to CFC-11 used in certain refrigerant and solvent applications (24).

The relative shares of projected CFC-11 output among the major worldwide producing sectors appear in Table 3-7 (2). These estimates assume an average of 3.0 percent growth in the United States, 3.0 percent in the EEC and other Western producers, and 2.0 percent in East Bloc countries. Rand has recently estimated a 3.3 percent annual growth on CFC-11 use, on a world basis, through 2000 (2), while another study has predicted worldwide consumption growth in the 4.0 to 5.6 percent range (25). In the absence of controls, CFC-11 use in industrialized nations other than the United States may grow more rapidly since aerosol applications are permissible. During this period the estimated doubling time for cumulative world CFC-11 production is about 15 years. According to a separate study, alternative scenarios for the growth of CFC-11 use suggest that the value for 2000 appearing in Table 3-7 may under-estimate projected use by 20 to 40 percent (25).

TABLE 3-7. PROJECTIONS OF UNITED STATES AND WORLD PRODUCTION OF CFC-11: 1985 - 2015

	Production in 1000 Metric Tons/Year (millions lbs./year)				
Year	United States	Europe, Other Major Producing Counties[a]	East Bloc Countries	World Total	Cumul. World Production since 1940[b] 1000 mt (million lbs)
1985	75 (165)	225 (496)	42 (93)	342 (754)	6332 (13960)
1990	87 (192)	271 (598)	46 (102)	404 (891)	8230 (18140)
1995	101 (222)	327 (720)	51 (113)	479 (1056)	10470 (23090)
2000	117 (258)	394 (868)	57 (125)	568 (1252)	13130 (28960)
2005	136 (299)	474 (1,046)	63 (139)	673 (1484)	16290 (35920)
2010	157 (346)	572 (1,260)	69 (153)	798 (1760)	20030 (44160)
2015	182 (402)	689 (1,519)	77 (169)	948 (2090)	24460 (53920)

Source: (2,23)

[a] Countries included in this reporting group are: Argentina, Australia, Brazil, Canada, England, France, Greece, Holland, India, Japan, Mexico, Netherlands, Spain, Venezuela, West Germany.

[b] Data prior to 1985 obtained from (23).

United States consumption of CFC-11 in flexible slabstock and molded foam in 1985, and projections through 2015 are shown in Table 3-8, and estimated projections for the world market are shown in Table 3-9 (2,24). Three scenarios are examined. For United States consumption projections through the year 2000, the base case reflects a combination of probable outcomes involving factors such as GNP growth and the extent of methylene chloride substitution for CFC-11. Clearly, numerous factors affect these growth projections, and uncertainties in these various factors result in low and high growth limiting cases as shown in the table. This span was stated to encompass an 80 percent likelihood range (2). Since molded foam usage is closely linked to growth in the automobile market, the base case projection for this material relies on auto industry sales growth projections of 1.9 percent annual rate in the United States and 2.9 percent abroad. The high and low growth cases for molded foam reflect uncertainties in predominant auto size, amount of CFC-11 blown foam used per vehicle, and in GNP growth. Projections through 2015 are extrapolations of the 1985 to 2000 period, adjusted to reflect other recent studies which suggest that the growth rate of CFC-11 demand will decline beyond the year 2000 (26).

One observation from Tables 3-8 and 3-9 concerns trends in the portion of CFC-11 output used in flexible foam manufacture between 1985 and the year 2015. This analysis suggests that growth in total use of CFC-11 will equal or exceed the growth due to flexible foam blowing. The fraction of CFC-11 output used for slabstock is projected to remain nearly constant through 2000, while the portion used in molded foam production is predicted to decline steadily. Contributing factors include increased use of methylene chloride and/or water-blown foams, and the current trend of decreasing molded foam volume used per vehicle.

TABLE 3-8. ESTIMATES OF CURRENT AND PROJECTED UNITED STATES USE OF CFC-11 FOR SLABSTOCK AND MOLDED FLEXIBLE FOAM: 1985 - 2015

		Slabstock				Molded			
Scenario	Year:	1985	1990	2000	2015	1985	1990	2000	2015
Base Case	Estimated Annual[a] growth, %	--	3.6	2.8	2.0	--	-0.4	-0.4	-0.3
	CFC-11 annual consumption, 1000 mt/yr	11.5	13.7	18.1	24.3	3.3	3.2	3.1	3.0
Low-Growth Limiting Case	Estimated annual[a] growth, %	--	-1.3	-2.1	-2.9	--	-3.2	-3.2	-3.1
	CFC-11 annual consumption, 1000 mt/yr	--	10.8	8.7	5.6	--	2.8	2.0	1.3
High Growth Limiting Case	Estimated annual[a] growth, %	--	8.7	7.9	7.0	--	2.5	2.5	2.6
	CFC-11 annual consumption, 1000 mt/yr	--	17.4	37.3	103.0	--	3.7	4.8	7.0
Base Case Consumption as percentage of projected U.S. Production of CFC-11[b]		15.3	15.7	15.5	13.4	4.4	3.7	2.6	1.6

[a] Indicated values used as approximate annual growth rates for the years between tabulated dates.

[b] As shown in Table 3-7.

Sources: (17,2, 26)

TABLE 3-9. ESTIMATES OF CURRENT AND PROJECTED WORLD USE OF CFC-11 FOR SLABSTOCK AND MOLDED FLEXIBLE FOAM PRODUCTION: 1985 - 2000

	Flexible Slabstock 1000 mt/yr (million lbs/yr)		Flexible Molded 1000 mt/yr (million lbs/yr)	
Year:	1985	2000	1985	2000
[a]Base Case	45.0 (99.2)	73.8 (162.7)	12.0 (26.5)	12.5 (27.6)
[a]Low Growth Case	--	42.5 (93.7)	--	7.8 (17.2)
[a]High Growth Case	--	130.8 (288.4)	--	19.7 (43.4)
[b]Base Case as percent of World Output of CFC-11	13.2%	13.0%	3.5%	2.2%

[a] See text for description of pertinent assumptions.

[b] Based on projected world CFC-11 production as given in Table 3-7, excluding East Bloc production.

Source: (2)

CHARACTERIZATION OF WORLD CFC-11 EMISSIONS

Ozone Depletion Potential

The ozone depletion potential for a given chlorofluorocarbon compound is expressed an an index value that reflects its relative theoretical contribution to destruction of stratospheric ozone. CFC-11 has been selected as the reference compound for this index, so its ozone depletion value is 1.0. All other chlorofluorocarbon compounds are ranked relative to CFC-11.

In relation to CFC-11 most other CFCs are considered to be less ozone depleting. Therefore, when comparing emissions and their relative effects, the CFC emissions should be weighted in regard to their theoretical ozone depletion potential. It is noteworthy that methylene chloride, a presently used substitute for CFC-11 blowing agent, has been assigned an ozone depletion value of nearly zero. This is because its residence time in the atmosphere, estimated to be less than six months, is short in comparison to CFC-11 which has a half-life in the atmosphere of 75 years or more. It has been hypothesized that methylene chloride breaks down readily in the lower atmosphere by reactions with hydroxyl radicals (27). For this reason, little or no methylene chloride would be transported into the stratosphere.

CFC-11 Emission Characteristics

A very small portion of total chlorofluorocarbon emissions are released during chlorofluorocarbon production. The primary sources of CFC emissions are the consuming industries. Comparison of relative release estimates reveals that flexible foam production contributes more than twice as much to annual CFC-11 emissions in the United States as does rigid foam production. This is because of the characteristics of CFC emission from these materials. The CFC-11 emissions from flexible foams are prompt, being released during or shortly after manufacturing is complete. The majority of emissions from rigid foams are banked. That is, the blowing agent is retained in the foam cells and emitted gradually over a long period of time, or is released when the material is destroyed at the end of its service life.

In flexible foam manufacture, design ventilation rates are specified within the foam tunnel to minimize occupational exposure to TDI. Depending on the size of the foam tunnel the ventilation rate may range from 6.5 to 45 Nm^3/sec (15,000 to 100,000 scfm). Vaporized blowing agents, TDI, and other unreacted chemical ingredients are discharged to the atmosphere in a highly dilute air stream. Details of blowing agent emission within a typical foam plant are discussed in Section 5 of this report.

Historical data, shown in Table 3-10, indicates that annual releases of CFC-11 are about 88 percent of annual production. This is because the nature of the major end-uses generally results in relatively prompt release. On a worldwide basis, more than half of all CFC-11 production in the largest producer nations is used as flexible foam blowing agents and aerosol propellants. About 35 percent of CFC-11 production is employed in rigid foam blowing, for which future releases are banked. But since a large reserve of previously manufactured foam exists in the environment this source accounts for about 10 percent of cumulative release (1,23,24). The remaining 15 percent of CFC-11 production is mostly used in refrigeration and miscellaneous uses.

Figure 3-2 visually demonstrates the predominance of promptly emitting uses for CFC-11. Restrictions on aerosol applications in the United States leave the flexible foam industry as the main emitter of CFC-11 in this country. The figure shows that since the mid-seventies, flexible foam production has been one of the fastest growing sources of CFC-11 emissions.

TABLE 3-10. CUMULATIVE CFC-11 CONSUMPTION AND RELEASE TO ENVIRONMENT ATTRIBUTED TO MAJOR END-USE CATEGORIES, Thousand Metric Tons (Million Pounds)

Year	Refrigeration		Rigid Foam Blowing Agent		Promptly Emitting Sources (Flex. Foam, Aerosols, Other)		World Total	
	Sales	Release	Sales	Release	Sales	Release	Sales	Release
1970	116	76	175	50	1426	1330	1692	1456
	(256)	(168)	(386)	(110)	(3140)	(2932)	(3730)	(3210)
1972	148	99	269	82	1879	1760	2262	1940
	(326)	(218)	(593)	(181)	(4142)	(3880)	(4987)	(4277)
1974	188	126	393	127	2444	2301	2981	2554
	(414)	(278)	(866)	(280)	(5388)	(5073)	(6572)	(5631)
1976	231	159	501	181	2957	2841	3635	3182
	(509)	(350)	(1105)	(399)	(6519)	(6263)	(8014)	(7015)
1978	283	199	632	248	3413	3322	4264	3769
	(624)	(439)	(1393)	(547)	(7524)	(7324)	(9400)	(8309)
1980	343	246	796	332	3777	3706	4843	4284
	(756)	(542)	(1755)	(732)	(8327)	(8170)	(10677)	(9444)
1982	395	299	989	435	4099	4038	5402	4771
	(871)	(659)	(2180)	(959)	(9037)	(8902)	(11909)	(10518)
1984	444	353	1198	556	4454	4386	6006	5295
	(979)	(778)	(2640)	(1226)	(9819)	(9670)	(13240)	(11670)

Source: (1)

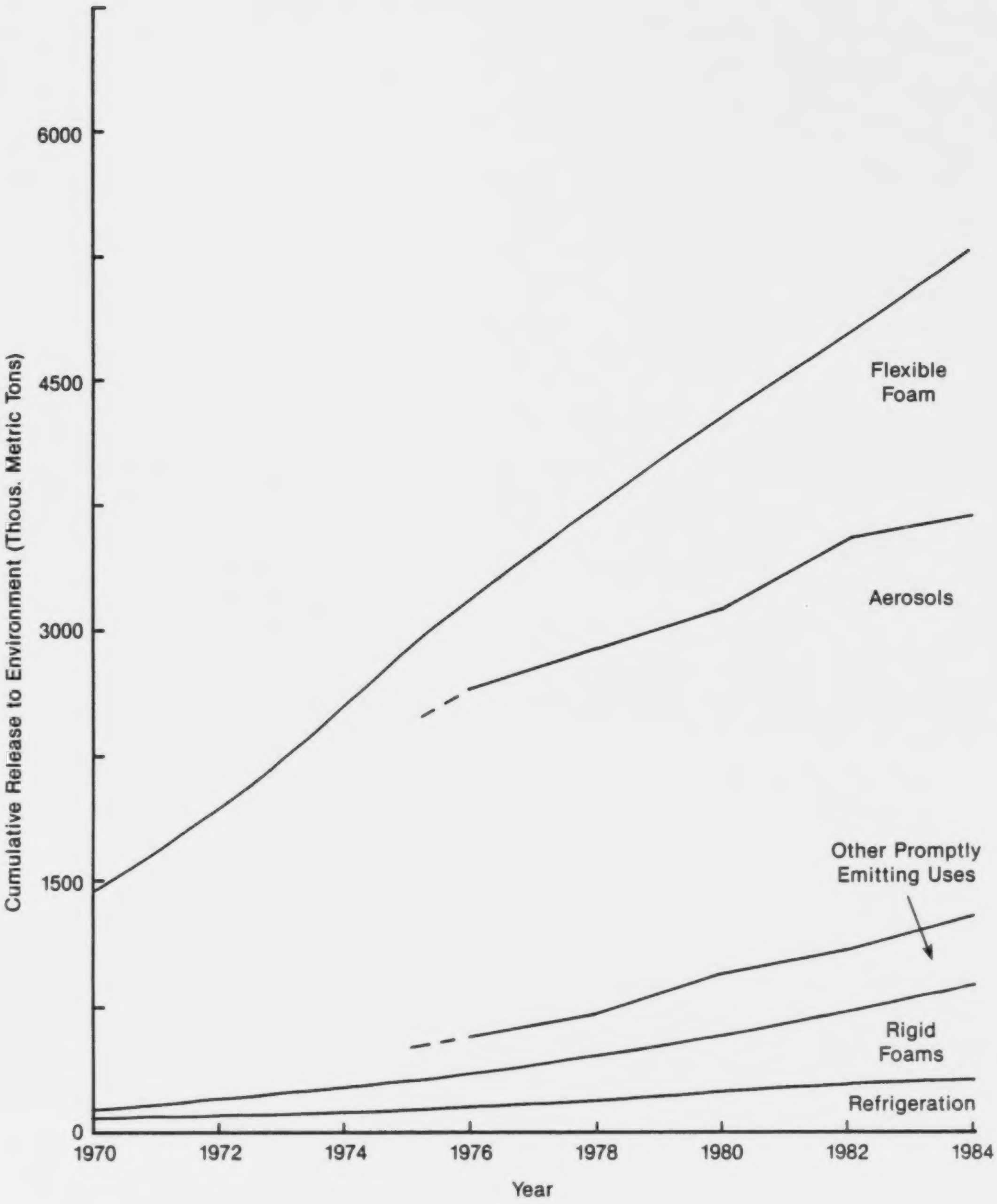


Figure 3-2. Cumulative CFC-11 releases to environment attributed to major end-use categories

Basis: Estimated releases from largest world producing nations; (1,24).

SECTION 4

CURRENT FLEXIBLE FOAM PROCESS TECHNOLOGY

POLYURETHANE FOAM CHEMISTRY

Principles of Flexible Foam Formulation

As mentioned previously, the most common formulating method for flexible foam formation is the one-shot process, in which the various components of the foam are simultaneously mixed and dispensed. This process was first developed in 1958, and is used in the preparation of flexible urethane slabstock and molded foam components. Typically, the foam formulation used will consist of a carefully specified mixture of polyether or polyester polyol, diisocyanate, surfactant, water, catalyst, an auxiliary blowing agent, and other miscellaneous additives. One of the outstanding characteristics of foam produced by the one-shot method is its versatility. By varying the proportions of certain components in the formulation, the manufacturer can build the desired end-use properties into the foam during production.

In both slabstock and molded foam processes, the foam formation mechanism consists of three steps:

1) Mixing and dispensing the foam components;

2) Cream period, during which the reactions initiate and liquid viscosity increases; and

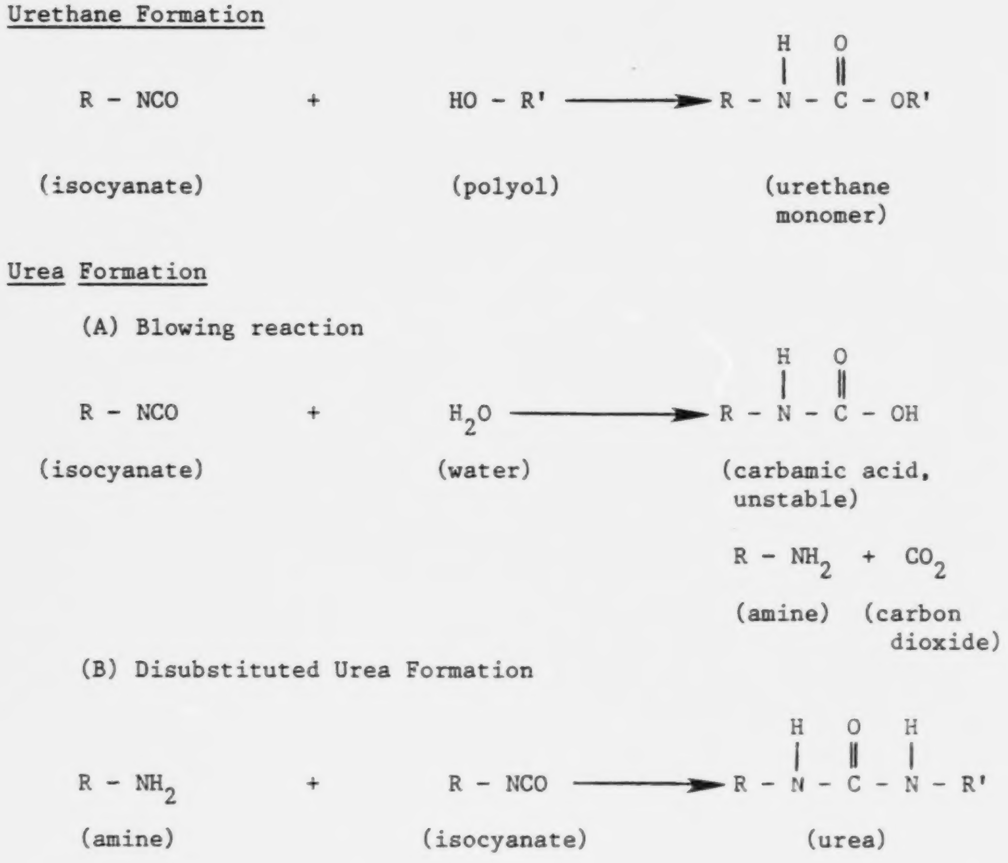
3) Rise period, in which the gelation (polymerization) of the urethane occurs simultaneously with the release of blowing agent(s).

During the rise period, the foam expands to its final density and solidifies.

The two major reactions involved in the chemistry of polyurethane foam take place simultaneously. These are the reaction of isocyanate with the polyol to form urethane monomers and of the isocyanate with water to form ureas and evolve carbon dioxide gas. Figure 4-1 shows the basic reaction equations (28,29,30). Subsequent chain addition and branching reactions involving other constituents of the urethane monomers (the "R" groups) result in the formation of polymer chains of varying lengths. Disubstituted urea compounds (those with two "R" groups) can form chemical linkages between the polyurethane chains which generally increases polymer chain rigidity. The extent of such cross-linking depends on the specific urea compound and its concentration, and on the amount of water in the foam formulation.

It is the extent of cross-linking that physically differentiates flexible foam from rigid polyurethane foams. Typically, the distance between these polymer chain interconnections in flexible foams is 10-30 times greater than in rigid foam polymers (30). Fewer polymer cross-linkages impart greater flexibility because the individual molecular chains are more easily deformed.

Although the nature of the chemical reactions involved is well known, the technology of polyurethane foam is quite complex. It is especially critical that polymer gelation and blowing agent release be closely coordinated. Specialized catalysts are employed to control the rates of the two main reactions. During the initial cream period, reaction of isocyanate and water forms unstable intermediates such as carbamic acid, which then break down to amine and carbon dioxide (31). This reaction must be kept in balance with urethane formation by isocyanate/polyol reaction in order to prevent foam collapse. During the rise period, polymer chain growth must also coincide with gas evolution within the foam matrix. If polymer growth proceeds too rapidly, the blowing agent gas pressure cannot break through the cell walls, thus forming closed cells which can result in a "doughy" foam.



Urethane Formation

$$\mathrm{R - NCO \quad + \quad HO - R' \longrightarrow R - \overset{\overset{H}{|}}{N} - \overset{\overset{O}{\|}}{C} - OR'}$$

(isocyanate) (polyol) (urethane monomer)

Urea Formation

(A) Blowing reaction

$$\mathrm{R - NCO \quad + \quad H_2O \longrightarrow R - \overset{\overset{H}{|}}{N} - \overset{\overset{O}{\|}}{C} - OH}$$

(isocyanate) (water) (carbamic acid, unstable)

$$\mathrm{R - NH_2 \quad + \quad CO_2}$$

(amine) (carbon dioxide)

(B) Disubstituted Urea Formation

$$\mathrm{R - NH_2 \quad + \quad R - NCO \longrightarrow R - \overset{\overset{H}{|}}{N} - \overset{\overset{O}{\|}}{C} - \overset{\overset{H}{|}}{N} - R'}$$

(amine) (isocyanate) (urea)

Figure 4-1. Major reactions in polyurethane foam formation. (R = general designation for portions of hydrocarbon molecules not involved in a specific reaction.)

The blowing agent gases (CO_2, CFC-11, or methylene chloride) must be evolved uniformly throughout the rising foam volume to produce a fine-cell structure. This requirement for uniformly dispersed gas bubbles precludes the use of an external source of carbon dioxide as the auxiliary blowing agent. There is no mechanically practical means to introduce an auxiliary gas into the rising foam bun, and carbon dioxide injected at the feed nozzle would not be entrained by the low-viscosity liquid.

In Table 4-1 examples of conventional flexible foam formulations are given for several grades of foam, including methylene chloride, water-blown, and HR foam (17,32,33). It is industry convention to base all such formulations on 100 parts polyol, so that the quantities of other components are stated relative to the polyol, which is the major constituent. From this table, it can be seen that a range of foam properties can be achieved by changes in formulation. Variation in catalyst and auxiliary blowing agent content have the greatest effect on the density and softness of foam produced from a particular polyol/isocyanate system. Catalyst formulations also differ for CFC-11 and methylene chloride blown foams.

Virtually every large foamer will develop specific formulations that yield the desired product quality at lowest cost. Small and moderate sized foam producers prefer to simplify their inventory by adopting a standard polyol/isocyanate combination. Numerous factors are involved in setting up the foam formulation, such as customer preferences, equipment tolerance, climate, and altitude. Also, small changes in humidity, barometric pressure, temperature, and batch variations in raw materials can affect the foam reactions. Generally, the skill of the operating crew determines how well a plant can cope with these transient conditions.

Proper choice of polyol is most important in that it permits the foam producer to tailor foams to desired specifications. It is the major constituent of the polymer backbone. Polyether polyols are most commonly used, and different classes of compounds are distinguished by their functionality, that

TABLE 4-1. EXAMPLES OF CONVENTIONAL ONE-SHOT FLEXIBLE POLYURETHANE FORMULATIONS

Type of Foam:	Medium-Density CFC-11 Blown	Medium Density Water Blown	Low Density Super-Soft	Low Density MeCl-Blown	Medium Density MeCl-Blown	HR Foam Medium Density
Ingredient	(parts per hundred parts polyol)					
Polyether Polyol	100	100	100	100	100	100
Isocyanate (TDI)	42.5	42.5	45.0	45.0	46.0	33.3
Water	3.5	3.3	3.5	3.4	2.6	2.7
Tin Catalyst	1.75	0.45	1.0	0.65	0.3	1.65
Amine Catalyst(s)	1.0	0.45	0.8	0.18	0.2	1.0
Silicone Surfactant	2.0	1.0	1.3	1.5	1.2	1.0
CFC-11	13.5	--	23.0	--	--	7.0
Methylene Chloride	--	--	--	20.0	10.0	--
Wt. Percent CFC-11	8.0	--	13.3	--	--	4.8
Foam Density, kg/m^3 (lb./ft.^{3})	22.4 (1.4)	28.8 (1.8)	16.0 (1.0)	16.0 (1.0)	25.6 (1.6)	32.0 (2.0)

Sources: (17,32,33)

is the number of hydroxyl (OH) end-groups present for reaction with isocyanate. Different polyol resin constituent groups can result in a wide range of strength and firmness properties. There are many polyols on the market to choose from, and new products are continually being introduced to meet the evolving needs of the foam industry.

Toluene diisocyanate (TDI) is the most frequently used isocyanate for flexible foam production. Recently, molded foam systems employing methylene diphenyl isocyanate (MDI) have also become available. These reagents provide the isocyanate group which reacts with both the polyol and with water. Based on the desired foam density, the formulation content of TDI may range from 25 to 60 parts per 100 polyol. A commercial mixture of 80 percent 2,4-isomer, and 20 percent 2,6-isomer is the most commonly employed TDI material, although blending with a 65 percent/35 percent isomer mixture is sometimes practiced to obtain modified reactivity.

Water also plays a key role in foam formation. It reacts with isocyanate to liberate CO_2, the primary blowing agent, and it contributes to the formation of urea linkages which enhance foam firmness. The water/isocyanate reaction is highly exothermic. Because of this, peak bun temperatures can be expected to range from 120°C (248°F) at 2 parts water to 170°C (340°F) at 5 parts water. The amount of water used in the formulation will, in part, determine the density and firmness of the foam. Foam density can be lowered with increased amounts of water (or auxiliary blowing agent) because gas evolution increases. Increased amounts of water will also contribute to formation of rigid polymer/urea cross-linkages which, in conjunction with density, determine foam firmness.

Amine catalyst, usually in the range from 0.1 to 1.0 parts per 100 polyol, accelerates the water/isocyanate reaction that releases CO_2, and also affects the extent of polymer cross-linking. A tin catalyst, generally stannous octoate, is added to accelerate the polyol/isocyanate reaction, that is, the urethane reaction. The latitude of tin catalyst concentration that can be tolerated is called the catalyst range. This is an important processing parameter; the wider the catalyst range, the easier it is for a foam producer to operate satisfactorily. Were it not for a synergistic interaction between the tin and amine catalysts, a wide operating range would be difficult to achieve. Catalyst activity also permits substitution of methylene chloride for CFC-11 blowing agent for certain foam grades, as will be explained in the next section.

Silicone surfactant stabilizes the foam while it is rising and controls cell size and structure. In slabstock production these surfactants also contribute to a more flat-top bun, by reducing surface tension and adhesion to the side walls of the foam tunnel. The introduction of silicone surfactants was perhaps the major factor that made possible the manufacture of polyurethane foam via the one-shot process, rather than going through an intermediate prepolymer step.

Softer and less dense foams are produced by incorporating volatile liquids as physical blowing agents. These compounds do not undergo reaction, but volatilize due to the heat liberated by the foam formation reactions. The gaseous vapors provide a physical means to lower foam density by creating additional void volume within the open cell structure. Also, the energy required to evaporate the blowing agent helps dissipate some of the heat generated by exothermic reactions within the rising foam. The chlorofluorocarbon content of the feed liquid may range from zero to perhaps 30 percent by weight depending on the density and softness properties desired (18,22). For the slabstock grades produced in largest volume, the CFC-11 content of the feed formulation ranges from 8 to 14 percent by weight.

Methylene chloride can be used as a substitute for CFC-11 as a blowing agent in slabstock production and depending on the catalyst used, can be added up to 25 parts per hundred polyol (27). Because of its lower molecular weight compared to CFC-11, about 15 percent less methylene chloride is required, by weight. However, complex technical and product quality limitations, which are discussed in the following section, prevent methylene chloride from being applied to all slabstock grades.

It should be emphasized that ability to achieve a range of foam density and softness properties depends on a precise balance of several formulating variables. In general, foam density and softness can be independently varied, that is, a low density foam does not necessarily imply high softness. Common practice is to set the foam properties by balancing the amounts of water and auxiliary blowing agent.

Blowing Agent Selection Factors

The most important characteristics of an auxiliary blowing agent for flexible polyurethane foam are a boiling point between 30 and 50°C, non-flammability, relatively low toxicity, and non-reactivity with other foam ingredients. Only two chemicals currently produced commercially meet these criteria and are reasonably economical to use: CFC-11 and methylene chloride. At present, state-of-the-art flexible foam technology limits selection of auxiliary blowing agents to these chemicals, or blended blowing agents containing one or both of these two compounds.

One important determining factor in physical blowing agent performance is the blowing gas efficiency. To illustrate the definition of this quantity, consider a bun at an assumed maximum temperature. It is possible to calculate a theoretical volume of blowing agent gas that would be liberated under this condition. But only a fraction of this theoretical amount will actually be converted to open cell volume within the foam. This fraction is referred to as efficiency of the blowing agent.

Differences in gas efficiency between carbon dioxide and auxiliary blowing agents result from differences in timing of agent volatilization with respect to the rates of polymer formation and cell rupture. Carbon dioxide evolved by the isocyanate/water reaction is more efficient than auxiliary blowing agents, and CFC-11 is a somewhat more efficient agent than methylene chloride. The primary reason why methylene chloride ranks below CFC-11 is due to its slightly higher boiling point, which delays volatilization. Another reason is the solvent power of methylene chloride; some of the added methylene chloride can be absorbed in the polymer cell walls. Several foam manufactures have noted that under some conditions, this property can cause the foam to remain "sticky" after solidification (27,34,35).

Advances in foam chemistry have allowed foamers to overcome these shortcomings of methylene chloride, especially in production of the more dense foam grades. The gas efficiency has been improved substantially by introduction of a delaying amine catalyst that slows polymer cross-linking until heat generation by the water/isocyanate reaction can volatilize the methylene chloride. Newly developed catalyst systems allow evolution of methylene chloride vapor and CO_2 to be precisely timed as is the case with CFC-11 and CO_2. This results in significantly higher gas efficiencies for methylene chloride, which expands its range of applicability. Without the proper catalyst, only 6 to 8 parts methylene chloride per hundred polyol can be tolerated in conventional foam formulations, but appropriate catalysts permit up to 25 parts (27). Foam discoloration and scorching was a problem when methylene chloride was initially applied; but newer urethane grade materials contain a stabilizer to minimize this tendency.

With respect to raw material costs, economic considerations currently favor methylene chloride over CFC-11, for all but the lowest density and softest foam grades. Previous studies have indicated that, for typical foams, average cost savings of up to seven percent of total raw materials cost are possible by switching blowing agents. This explains, in part, why more than half of all slabstock facilities currently use this agent to some extent (3,5). Two main factors are at work. First, due to its lower molecular weight, methylene chloride yields a greater volume of gas per unit weight. The weight of methylene chloride required is about 85 percent of the CFC-11 needed for comparable formulations. Secondly, the price for CFC-11 has historically been higher than that of methylene chloride; the differential is currently about $0.30 to $0.40 per kg ($0.15 to $0.20 per pound) (36,37).

Selection of an auxiliary blowing agent is driven as much by the subjective opinion of the individual foam producers as by technical and economic factors. The switch from CFC-11 usually requires some development effort to obtain equivalent quality, so the foam producer may have to accept temporarily increased scrap rate and initial reformulation costs. Other intangible factors involved in the decision to employ methylene chloride include the ability of the operating staff to reliably control product quality with the more sensitive formulations, quality perceptions of customers, adequacy of plant ventilation, and worker safety.

For molded foam production, CFC-11 is used exclusively as the auxiliary blowing agent because the higher boiling point of methylene chloride causes more of the material to be retained in the mold, increasing the detrimental effect of the agent's solvent strength. In the past, CFC-11 was used to some extent for virtually all molded foam components; as much as 8 to 12 weight percent for components, such as auto seat backs, for which higher softness is specified (37). More recently, the consumption of CFC-11 for molded foam production has declined, especially in the automotive industry, due to the increased use of water-blown systems and the trend toward slightly firmer foams and smaller cars and seats (2,15).

FLEXIBLE SLABSTOCK FACILITY OPERATION

Plant Layout and Operation

The commercial process for flexible polyurethane slabstock has been well developed over the last 20 to 25 years. A schematic flow diagram of a typical manufacturing operation is shown in Figure 4-2. At the head of the foam tunnel the foam components are continuously premixed and fed either through a traversing head or into a foam trough as a liquid. Within a few seconds, the material immediately begins to cream and rise due to exothermic reactions described in the previous section. The foam is carried down an inclined, moving conveyor constrained within side panels. Moving paper and/or plastic

1) Chemical storage; 2) Miltiple-stream metering and mixing head; 3) Traversing dispersing head (if used); 4) Feed trough (Max-Foam®); 5) Conveyor enclosure with exhaust fans and stacks; 6) Top surface wrapping rolls (optional); 7) Side paper take-off rolls; 8) Botton liner paper roll; 9) Bun saw exhaust hood; 10) Bun saw and operator station

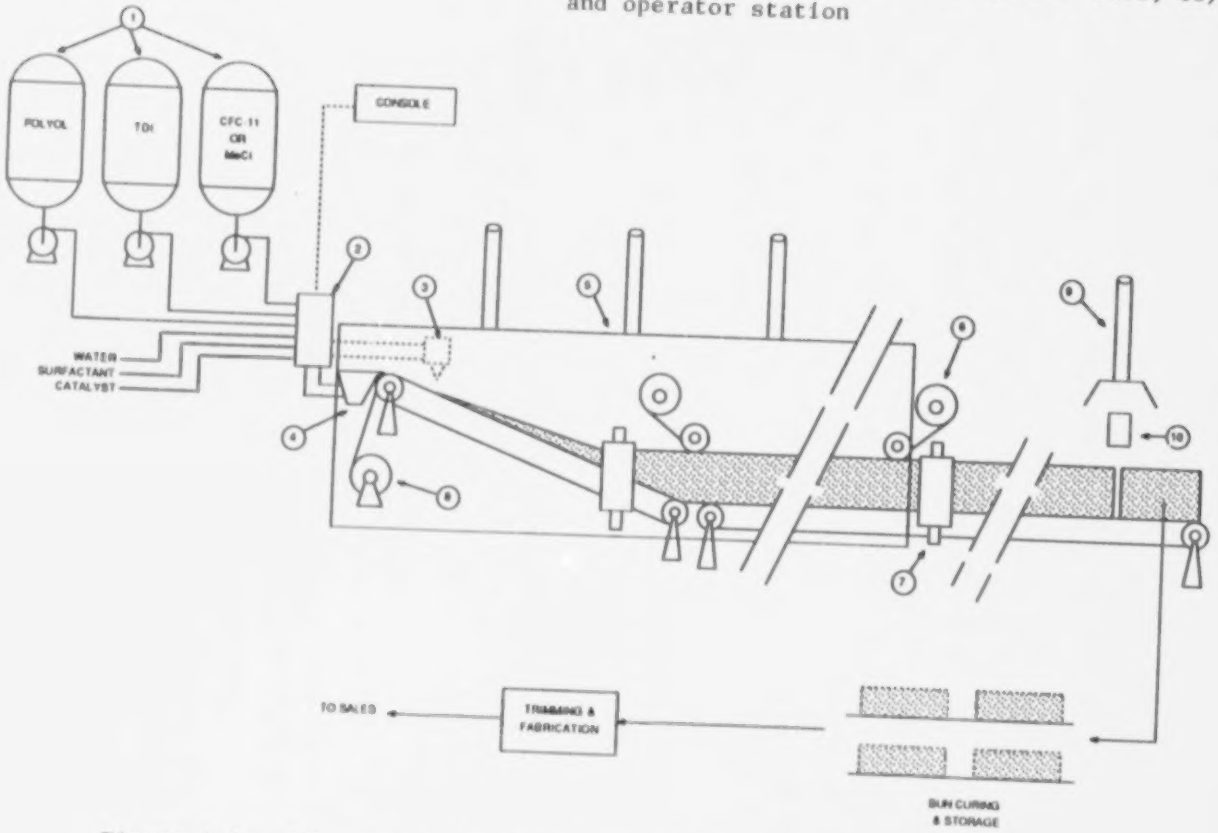

1
POLYOL
TDI
CFC-11 OR MeCl
CONSOLE
2
3
4
5
6
7
8
9
10
WATER
SURFACTANT
CATALYST
TO SALES
TRIMMING & FABRICATION
BUN CURING & STORAGE

Figure 4-2. Schematic of Typical Flexible Polyurethane Slabstock Production Line

sheeting wraps are used to line the bottom, sides, and in some older configurations, the top of the foam path. At some installations the rigid side panels of the conveyor are adjustable to permit a bun width between about 1 to 2 meters wide and 1 to 1.5 meters high.

The rising foam bun approaches its maximum height inside the enclosed foam tunnel, typically within four minutes, or about 18 meters (60 feet) down the foam conveyor. Due to the higher boiling point of methylene chloride, foam gelation must be delayed to allow internal heat generation in the foaming mass to volatilize the blowing agent. As a result, significant methylene chloride emission can occur outside the confines of the foam tunnel. Therefore, to maintain appropriate methylene chloride levels in certain plant areas higher ventilation rates may be required than those for CFC-11 use.

For either blowing agent, additional conveyor length is needed beyond the foam tunnel to permit the foam to solidify so that it can be handled. At the end of the conveyor the buns are sawed into convenient lengths, generally between 3 to 10 meters, for temporary storage in a curing area. This curing step allows the polymerization reactions to come to completion, and the buns to cool prior to final trimming and/or fabrication.

There are numerous styles of commercial foaming equipment. Each is designed by the equipment supplier to accept a range of foam formulations, as specified by the foam producer. Generally, the tolerance of the feed mixing and dispensing equipment depends on the viscosity of the dispensed liquids, and the required delivery temperature and pressure (10,38). As many as six individual streams must be metered, mixed, and dispensed simultaneously. The equipment for this task is usually the most sophisticated and expensive in typical foam plants, representing a major portion of a producer's capital investment. An important advantage for slabstock forming equipment is the capability to deliver a flat-topped bun, which reduces trimming waste. For this reason, trough feed equipment (Max-Foam® type) is highly favored over the older traversing head dispensing equipment (10).

Once the foam formulation is established, close supervision is required to make critical adjustments for changes in humidity, atmospheric pressure, temperature, dissolved oxygen or other random variations in raw material quality. The duration of an individual foam run may vary from a few minutes to several hours, with production rates that can exceed 250 kg/min. At this rate the raw materials cost may exceed $500 per minute (32), so quick response to changes in process conditions is essential to profitability. This also explains why foamers will develop strong prejudices regarding particular foam formulations and blowing agents; just a few minutes of unsaleable product can offset the profit for a production run.

Flexible slabstock is produced in a wide range of densities; the largest volumes are in the 12-48 kg/m^3 (0.8-3.0 lb/ft^3) range. In recent years the market trend has been to lower density slabstock foams, which would contribute to greater CFC-11 use (19,39).

With the exception of perhaps the largest foam manufacturing concerns, slabstock foam companies tend to be undercapitalized operations. Nearly all the necessary technical expertise is available from equipment and chemical suppliers, so small and moderate sized foam plants do not maintain an in-house staff to coordinate complex processing procedures. Profitability of such facilities is often marginal, and a small foam producer's market position is always uncertain. All of these factors tend to mitigate against implementation of costly or technically complicated emission control technology in these plants.

CFC-11 Emission Characterization in Slabstock Plants

Chlorofluorocarbon emissions from a slabstock plant are diluted with large volumes of ventilation air within the plant environment. Foam plant ventilation is usually designed to accommodate process emissions of TDI, which has a TLV of only 0.02 ppm. As a result of this, the exhaust air stream is generally quite dilute in CFC-11, seldom exceeding a few thousand ppm. Plant worker health is not usually an issue when CFC-11 is used since the TLV of this material is 1000 ppm. However, health questions remain unresolved regarding methylene chloride, for which the currently accepted TLV is 500 ppm (40).

The CFC-11 blowing agent is usually present at dilute levels in ventilation streams from the foam manufacturing area, although there are certain locations where emissions are distinctly more concentrated. A summary of ambient air CFC-11 concentration ranges observed at representative facilities is shown in Table 4-2. The ranges in CFC-11 level are indicative of plant-to-plant variations, differences in foam being produced and the sensitivity of the detection techniques used. In general, it can be observed that the CFC-11 levels are highest near open ends of the foam tunnel. Higher levels are noted for super-soft and/or low-density (i.e., less than one pound per cubic foot) foam production, as a direct result of the increased amounts of blowing agent used. One study has noted that the highest levels were measured at the feed dispensing head and at the side paper take-off close to the bun (13).

Table 4-3 illustrates the ranges of CFC-11 emissions measured in process exhaust air from the foam tunnels at four representative plants. Over a fairly comprehensive range of CFC feed rates and ventilation flows the CFC-11 concentration does not exceed a few thousand parts per million. An indication of potential CFC recovery can be obtained from material balances comparing exhaust emissions with the CFC-11 contained in the original formulation. This represents the maximum recovery potential if add-on emission controls were applied without modifying current ventilation practice.

As shown in Table 4-3, the percentage of recoverable CFC appears to depend on the volume of air exhausted through the tunnel, and tunnel residence time. This is suggested by the nine percent collection efficiency at Plant C, with only 3.9 Nm^3/s exhaust flow (9000 cfm), as compared to 33 to 53 percent at Plants A, B, and D, having 11 to 15 Nm^3/s flow (25,000 to 35,000 cfm). Also, if the tunnels were lengthened to enclose more of the conveyor line, the portion of CFC collected could be increased; note the higher percentage collected at Plant D (43 meters) relative to Plant B (20 meters).

TABLE 4-2. SUMMARY OF DATA ON CONCENTRATION OF CFC-11 IN VARIOUS AREAS OF POLYURETHANE SLABSTOCK PLANTS (IN PPMV)[a]

	Published Data		Unpublished Industry Data		Data From Radian, 1982	
	Super Soft	Standard	Super Soft	Standard	Super Soft	Standard
Mix Area	88-178	62	100-1138	5-45	1000	
Feed Dispensing						
- Front	139-146	31	52-137	32-121	150	
- Middle	182-198	25	59-77	17-19	500	12-15
- End	156-181	24	89-5694	17-225	3000-5000	
Side Paper Take-Off			105-1627	10-250	1500-10000	75-200
Top Paper Take-Off (optional)			110-2802	127		
Conveyor			154-2429			
Cut-Off Saw	130-181	15	38-1783	5-454		200
Curing Racks	355-586	280	486-686	42-420		
Product Storage	<10	<10				
General Building	47-60	26			50	
Packaging/Shipment	<10-95	<10		100		
Laboratory/Office				15		

[a] Data given for super soft (1.0 lb/ft. or less) foam and standard grade foams.

Sources: (13,41)

TABLE 4-3. SUMMARY OF DATA ON COLLECTION OF CFC-11 IN POLYURETHANE SLABSTOCK PRODUCTION TUNNELS

Plant ID	Tunnel Length (feet)	Tunnel Length (meters)	Residence Time (minutes)	Product Type (kg/m^3)	Total Exhaust (Nm^3/s)	CFC Charge (kg/min)	CFC Concn. (ppmv)	% CFC collected[a]
A	120	37	6.7	Super soft	15.1	2.3-13.3	200-300	53
B	65	20	5.9	Super soft	10.8	9.2	500-2000	33
C	135	41	9.8	Super soft	3.9	4.2	200-300	9
D	140	43	9.3	Super soft	10.8	28.0	800-2500	29-46
D	140	43	9.3	Low density (16-21)	10.8	11-14	100-500	41-48
D	140	43	9.3	Medium density <32	10.8	4-6.4	<300	23

[a] CFC collection is defined as the percent of CFC used in the formulation which is released from the foam and captured in the foam tunnel exhaust air system. Excludes potential recovery at cutoff saw.

Sources: Unpublished industry data; (13).

Data from previous tests at two plants show that the CFC concentration in foam tunnel exhaust can also be correlated with the amount of CFC used (13). These data, shown in Figure 4-3, suggest that a higher percentage of the CFC-11 is released in the foam tunnel when using low density foam formulations richer in CFC. This may be attributed, in part, to more rapid diffusion of the gaseous blowing agent out of the cells in low density foams.

Potential for Control Application

Since 1976, United States annual consumption of CFC-11 for slabstock production has averaged 11.7 thousand mt/yr (25.8 million lbs/yr). The largest non-U.S. world producers of flexible foam (e.g. Western Europe, Japan) have used an average of 35.8 thousand mt/yr (78.9 million lbs/yr) during this same period. These quantities represent 15.6 and 10.5 percent, respectively, of total United States and world CFC-11 consumption (2).

Emissions of CFC-11 from flexible foam manufacture are dependent on the density and/or softness grade of the foam product and the volume of those grades produced. To illustrate, Figure 4-4 depicts the incremental and cumulative emissions as a function of foam firmness, expressed as the ILD[1] index, associated with average slabstock densities of 21 to 24 kg/m^3 (1.2 to 1.5 lb/ft^3). These results are based on 1985 CFC-11 usage, and assume typical firmness grade distribution (from Figure 3-1) and CFC-11 content. The figure shows that the largest incremental emission reduction potential is associated with medium firmness foam (20 to 30 ILD) even though more CFC-11 is used per unit of softer foam. Nearly all CFC-11 emissions from slabstock plants, and therefore most of the cumulative curtailment potential is associated with foams having ILD less than 35.

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[1] ILD = Indentation Load Deflection, is a key firmness specification for flexible foam. It refers to the force (in English Units) required to compress a foam sample a set percentage, typically 25 percent, of its height. The softest foam grades have an ILD of 10 or less, the most firm greater than 40.

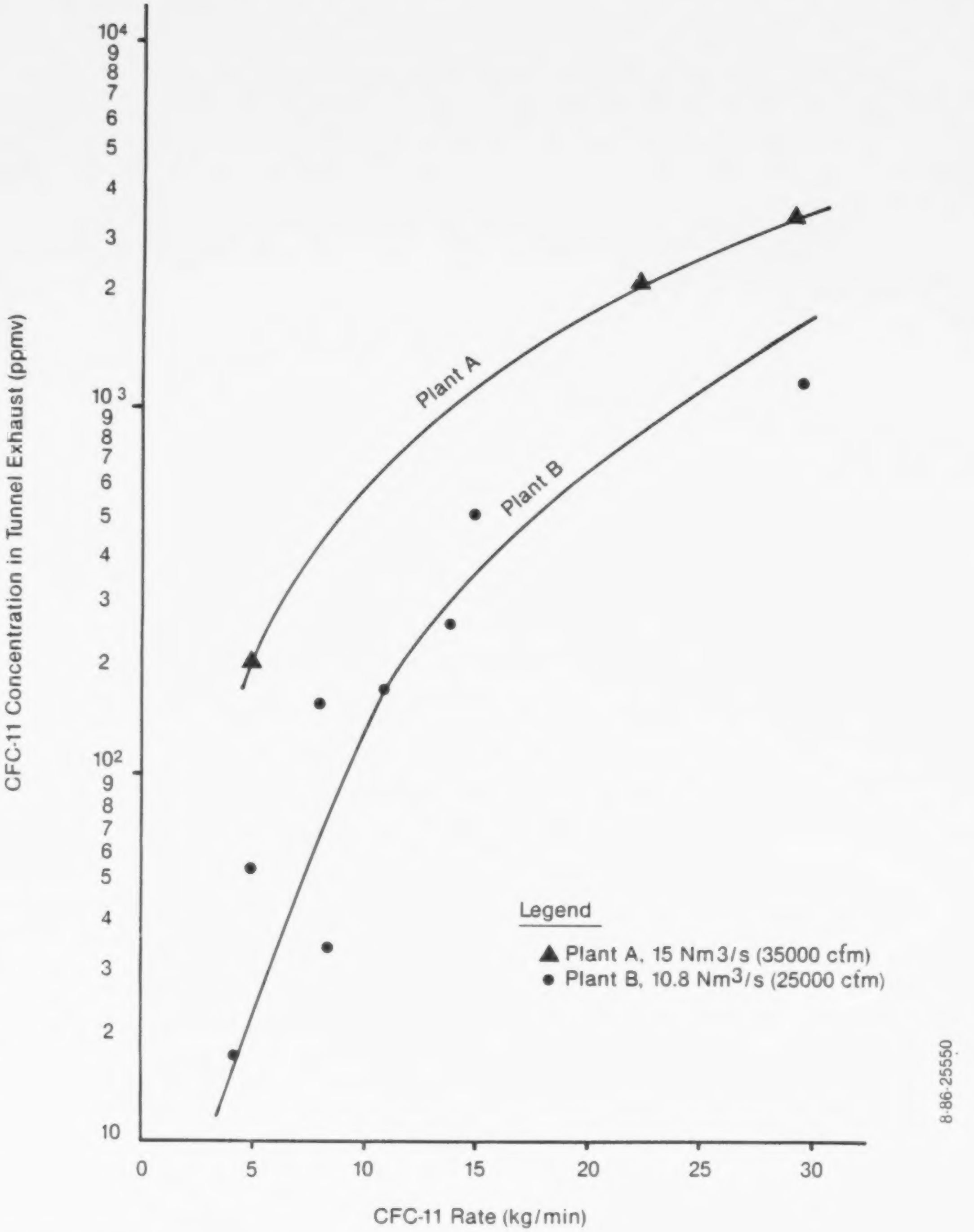


Figure 4-3. Relationship between CFC-11 exhaust concentration and foam line feed rate for two representative slabstock plants.

A number of control technologies are presently available to reduce CFC-11 from flexible foam manufacturing facilities. For example, carbon adsorption of CFC-11 from plant exhaust, followed by steam stripping and recovery of CFC-11, has been investigated (37,38,39). CFC-11 emission was reduced 40 percent by this technique in a recent short-term pilot demonstration in Denmark, and process modifications have been proposed to improve recovery (13,42). However, a number of technical issues, such as fouling of the carbon bed by isocyanate residues and other contaminants, must be resolved. The economics of this process may be unfavorable, because the large capital investment is difficult to recover solely from the recovered material credit. Also, additional purification may be needed before the recovered CFC-11 can be reused, and there will be a cost for disposal of steam condensate and regeneration or replacement of fouled carbon.

The concentration of CFC-11 in process exhaust streams is a key factor in economical adsorption/recovery of CFC-11. As shown in Figure 4-3, these concentrations are somewhat higher for higher feed concentrations of CFC-11, such as are used for low-density, high-softness foam grades. It would appear, then, that it would be more economical to recover a higher percentage of the CFC used for super low-density grades, as opposed to moderate density foams. This same conclusion was reached in an earlier study (35). However, the softer grade foams make up a small portion of the production volume at typical foam plants (see Figure 3-1), so the actual reduction in emissions may not be large.

Use of methylene chloride as a substitute blowing agent for CFC-11 is an established technology. As of 1985, over half of the operating flexible slabstock plants employed methylene chloride to some extent (3). In instances where methylene chloride is used, CFC-11 may be excluded from the foam formulation, so all CFC-11 emissions are avoided. Unfortunately, there are some significant technical problems with using methylene chloride as an auxiliary blowing agent, particularly for low-density foam grades. Also, while there are still many unresolved issues regarding the human toxicity and carcinogenic hazard of methylene chloride, worker protection measures can maintain exposure

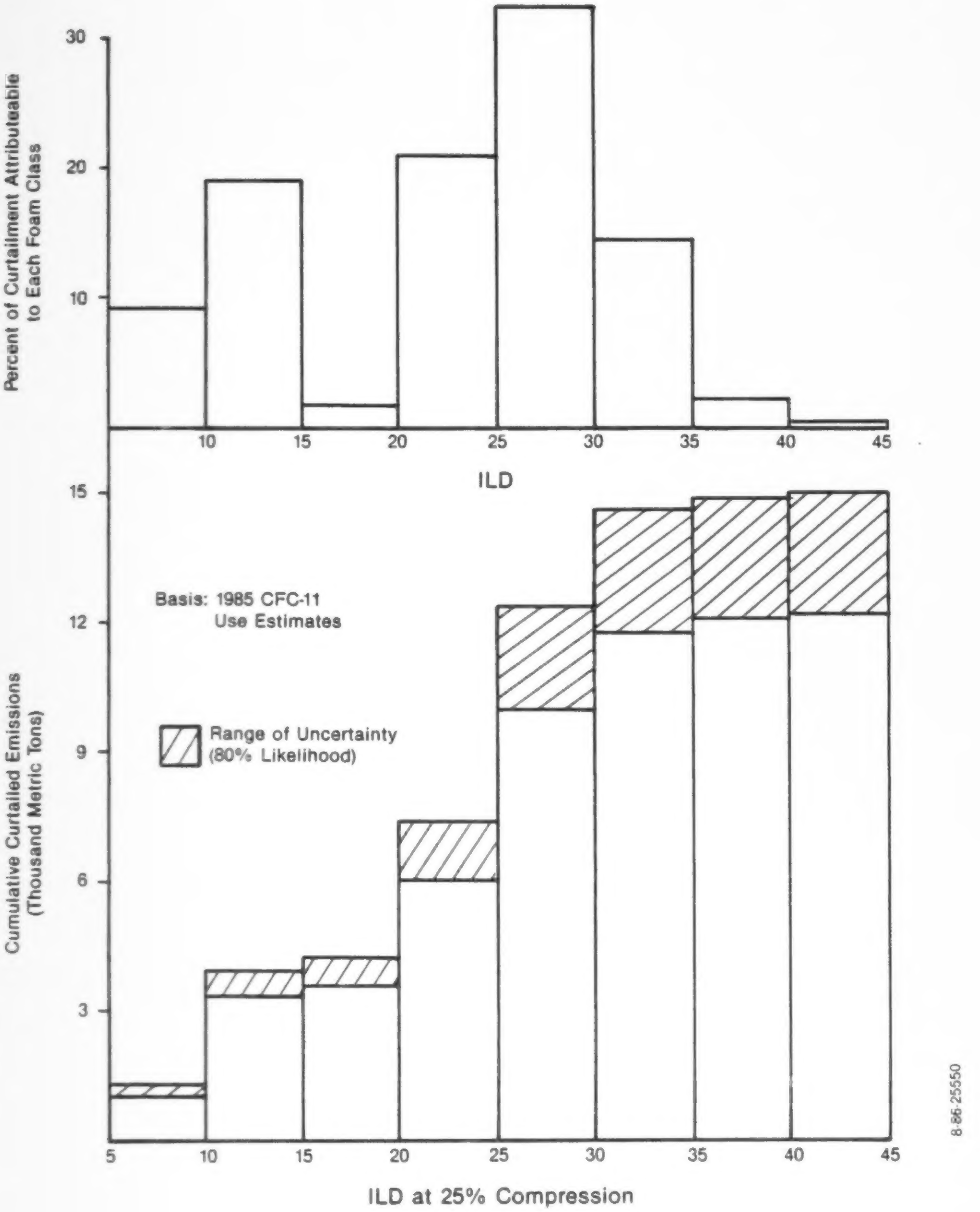


Figure 4-4. Potential for CFC-11 emission curtailment as a function of firmness classification.

Sources: (1,2).

levels below those likely to constitute a hazard. Blends of CFC-11 with methylene chloride and other volatile hydrocarbons are also produced commercially for use as foam blowing agents as substitutes for CFC-11.

An increase in the average density of flexible polyurethane foams represents a straight forward product modification that could significantly reduce use of auxiliary blowing agents. In general, the amount of auxiliary blowing agent used increases as foam density decreases, and methylene chloride use is often not practicable for lower density foams. As a result, most of the CFC-11 blowing agent consumption is attributable to the manufacture of low density foams. While there are few, if any, technical barriers to this control measure, it would be important to consider potentially severe effects on foam demand, competitiveness of end-products, and secondary effects such as increased energy consumption. Also, a shift to higher average density foams would require some adjustments and retooling in end-use industries.

Other control categories, such as alternative foam processes, new CFC-type blowing agents, and product substitutes, offer somewhat longer-term promise for reducing CFC-11 emissions. These alternatives have good potential for CFC reduction as future developments occur. In particular, several new chemical technologies of interest are discussed in Section 8 of this report. Most of these processes are in the developmental stages, or are just beginning to penetrate the commercial market.

MOLDED FLEXIBLE FOAM FACILITY OPERATION

Plant Layout and Operation

Molded flexible polyurethane foam is used primarily in the automobile industry as seat cushions and backs, and in furniture manufacture. Two processes are currently in use, namely, the hot molding process and the cold molding or high resilience (HR) process. Both processes involve numerous processing steps, and in larger plants it is common for the line to be computer controlled to maintain quality control.

In the hot molding process depicted schematically in Figure 4-5 the molds are usually mounted on a carousel belt and are rotated through the operation cycle in a continuous manner. The molds may be constructed of aluminum, carbon steel, or fiberglass resin, and several different components can be produced on a single carousel. As shown in the figure, the mold is first cleaned, usually with methylene chloride solvent, and a release agent applied. Support wires or supplementary springs may then be inserted if required. A precise amount of raw materials is delivered to the mold at a specified temperature and pressure via a movable mixing/dispensing head, and the mold is closed. As the foam reactions initiate, the mold is conveyed into a cure oven. In the cure oven the foam reactions are substantially completed and the foam fills the mold. At the exit of the cure oven, the fully expanded piece is removed from the mold, or demolded. Most molded products are crushed by rollers after removal from the mold. This causes additional cell rupture, giving the foam open-cell characteristics. The total cycle time for the hot molded process is approximately 30 minutes (3).

The HR molded process, shown schematically in Figure 4-6, was developed in the early seventies as a more economical alternative to hot molding. Improvement in the catalysts used and utilization of a more reactive polyol system permit HR foams formulations to internally generate sufficient curing heat. Operation of the high resilience (HR), or cold cure, process is similar to the hot molding process, except that external heating is not required for polymer gelation and foam curing. However, the molds are usually pre-heated before filling with feed liquid. And, in some cases this process includes a post-cure heating step, to dry the demolded part, and improve the surface skin finish of the "green" molded part. An inherent advantage of the HR process is shorter curing times which permit more rapid demold, and about 50 percent reduction in cycle time (33).

In recent years, HR formulations have come to dominate the molded foam industry, such that the older hot-molding process is essentially obsolete. Numerous innovations have expanded the versatility of components produced by the HR process. One example is the introduction of MDI-based foam systems

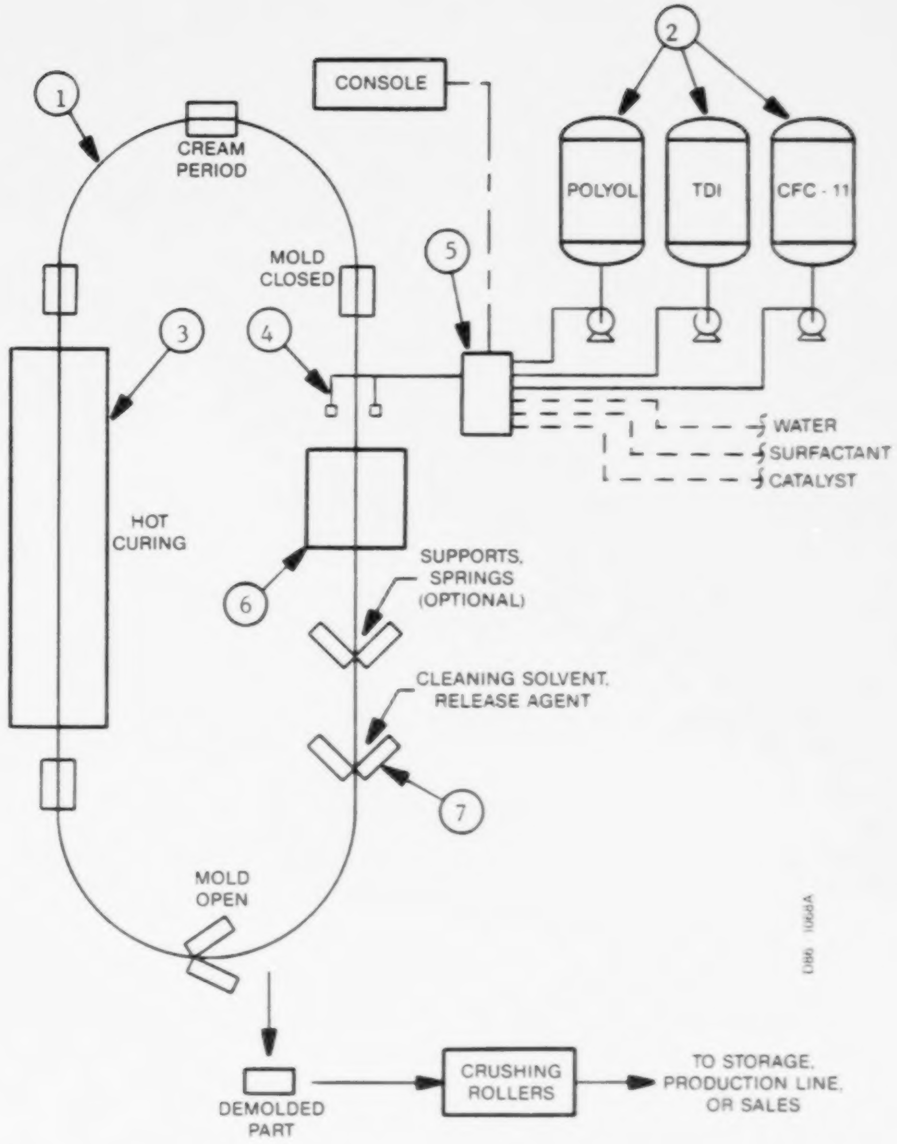

2
CONSOLE
1
CREAM PERIOD
POLYOL
TDI
CFC - 11
MOLD CLOSED
5
3
4
WATER
SURFACTANT
CATALYST
HOT CURING
6
SUPPORTS, SPRINGS (OPTIONAL)
CLEANING SOLVENT, RELEASE AGENT
7
MOLD OPEN
D86 1068A
DEMOLDED PART
CRUSHING ROLLERS
TO STORAGE, PRODUCTION LINE, OR SALES

Figure 4-5. Flexible polyurethane hot-molded foam process.

1 - Automated mold carousel; 2 - Chemical storage; 3 - Infrared curing oven; 4 - Feed dispensing/mold filling station; 5 - Multiple-stream metering machine; 6 - Mold pre-warming station; 7 - Typical mold, aluminum, carbon steel, or fiberglass resin

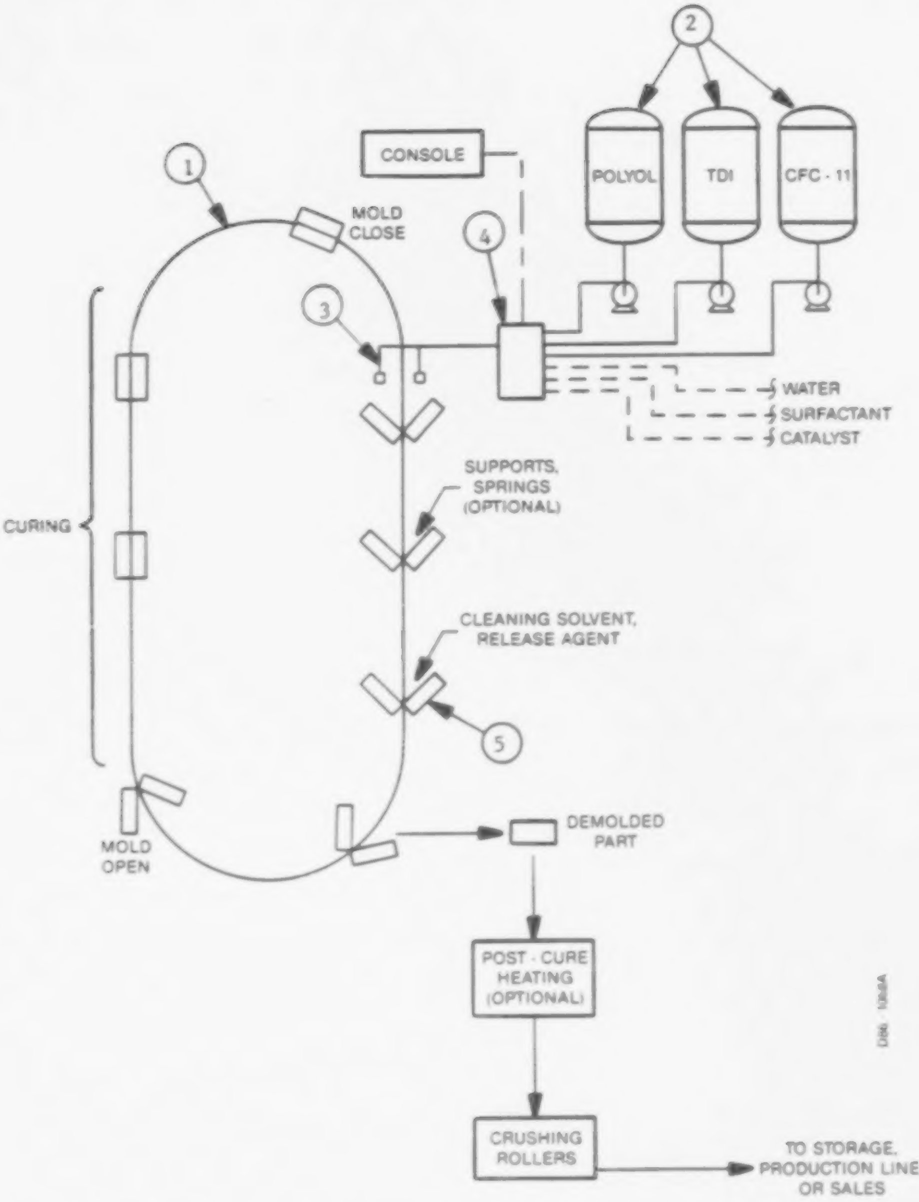

2
POLYOL
TDI
CFC - 11
CONSOLE
1
MOLD CLOSE
4
3
WATER
SURFACTANT
CATALYST
SUPPORTS, SPRINGS (OPTIONAL)
CURING
CLEANING SOLVENT, RELEASE AGENT
5
MOLD OPEN
DEMOLDED PART
POST - CURE HEATING (OPTIONAL)
CRUSHING ROLLERS
TO STORAGE, PRODUCTION LINE, OR SALES

Figure 4-6. Flexible polyurethane HR (high resilience) molded foam process.

1 - Automated mold carousel; 2 - Chemical storage; 3 - Feed dispensing, mold filling station; 4 - Multiple-stream metering machine; 5 - Typical mold, aluminum, carbon steel, fiberglass resin

which offer benefits in process operation and have expanded the range of load-bearing properties for HR foams (21,39,43). Composite automobile seats comprised of several sections, each with different load-bearing properties, is another recent development (43). Molded HR foams are produced over a wide range of densities and firmnesses. Most of the material now used by the United States auto industry is in the 29-40 kg/m^3 (1.8-2.5 lb/ft^3) range (11,43); molded HR foam furniture components for residential furniture are predominantly in the 24-32 kg/m^3 (1.5-2.0 lb/ft^3) range with higher density grades generally used in higher-priced furnishings (19).

Most large volume molded foam parts such as automobile seats and furniture components use CFC-11 blowing agent to some extent. For economic reasons and ease of manufacturing, CFC-11 may constitute 8 to 12 weight percent of certain formulations (37,39). However, sufficient formulation technology is commercially available to produce the entire range of molded HR foams without the use of CFC-11.

Because of the greater processing complexity of molded foam parts, the manufacturing equipment is more sophisticated than in slabstock plants. Often the production carousel is computer controlled to maintain tight quality control. The largest single end-use for molded foam is in the automotive industry, and most of the output is produced captively by the large auto manufacturers. For these reasons, molded foam plants are generally highly capitalized, and technical expertise is available to optimize process operation.

CFC-11 Emission Characterization in Molded Foam Production

Because commercial molded foam facilities are usually in operation more or less continuously for one to three shifts per day, the CFC-11 emissions are more constant than from a slabstock line which might run for limited periods of time. This means that there is a continuous, relatively uniform CFC-11 emission stream. As in the case of slabstock plants, high ventilation rates are dictated by isocyanate exposure requirements; therefore, when CFC-11 is used, its concentration in process exhaust is very dilute.

Relatively little test data on CFC-11 emissions have been collected for molded flexible polyurethane plants. Table 4-4 provides a profile of CFC-11 emissions as a percentage of the blowing agent used in the formulation, for both the hot molding and HR molded foam processes. Material balances around these plants could account for over 90 percent of the total CFC emissions (13). On a mass basis, almost a third of the chlorofluorocarbon emissions in the hot process occur within the curing oven, with another third emitted during the post-cure and foam crushing operations. In the HR process, a much larger percentage of the initial CFC-11 feed is released during demolding and post-cure heating operations.

Concentration data for specific process exhaust lines in a representative hot molding foam plant appear in Table 4-5. The two columns represent different studies in the same facility, the discrepancies between measured CFC-11 concentrations can be attributed to differences in the amount of CFC-11 in the formulation at the time of measurement, and variations in sampling technique. Both sets of measurements agree that the highest concentrations are found in exhaust from the curing oven, mold opening, demold, and crusher stations.

Potential for Control Application

The total quantity of CFC-11 used to produce molded flexible foam in the United States was estimated to be 3.3 thousand metric tons (7.3 MMlbs) in 1985 (1). This is a little more than 25 percent of the amount used in slabstock foam production. Consumption for this end-use has actually declined since a peak in usage of 4.3 thousand metric tons in 1978-79 (2). This reduction has been attributed to increased use of HR formulations, in conjunction with a trend toward firmer foams which require less CFC-11 per unit weight.

The molded foam process appears to be a poor candidate for add-on CFC-11 emission control systems. The process ventilation streams are too dilute for

TABLE 4-4. CFC-11 EMISSION PROFILE FROM MOLDED POLYURETHANE FOAM OPERATION

	Hot Molding	HR (High Resiliency)	
Foamer Head	1%	Dispensing	8-10%
Mold Close	2.5%		
Ovens	30%	Rising/Cure	3-5%
Mold Open	9.0%		
Before Debun	1.5%	Debun/Demold	25%
Debun	6%		
Demold	9%	Post Cure (heating)	40%
Total From Molding Line =	59%		
Crusher	15%	Crushing	15%
Post Cure	18%	Storage/Sales	5%
Total Emissions Accounted For	92%		

Source: (13)

TABLE 4-5. CONCENTRATION OF CFC-11 IN EXHAUST STACKS AT A MOLDED FLEXIBLE URETHANE FOAM FACILITY

Process Operation	CFC Concentration (ppmv) In-Plant Study	Radian, 1982
Foamer Head	12-15	20
Mold Close	100-122	21
Oven Entrance	167	30
Oven - Zone #1	73-158	15-36
Zone #2	46-82	13-32
Zone #3	46-67	15-32
Zone #4	118-172	31-40
Zone #5	137-212	31-41
Debun	67-87	18
Molds Open	200	29
Demold	45-73	24
Crusher	333-550	27-28

Source: (13)

effective recovery, and more thorough enclosure of the carousel or process line is difficult. This is because manual procedures are necessary at several points in the process, and sufficient ventilation rates must be maintained to protect personnel from contact with excessive TDI or MDI concentrations.

Substitution of methylene chloride is not favored for molded foam production, since retention of the blowing agent in the mold can result in foam collapse, or cause the finished product to have a tacky surface.

As is the case with slabstock foams, short-term reductions in CFC-11 use could be achieved by increasing the average density of molded foam components. But the potential percentage reduction in use by this measure is lower than for slabstock production. This is because, on average, molded components are of higher density, and already use less CFC-11 per unit foam, than flexible slabstock foams.

A more likely prospect for eliminating CFC-11 emissions from molded foam blowing is substitution of entirely water-blown formulations using TDI or MDI reagents. Commercialization of these systems is more advanced in Europe than in the United States (11,15). However, chemical systems currently available promise substantial expansion in the range of properties achievable without CFC-11 blowing agent. Systems that can produce essentially all currently used molded foam grades without CFC-11 are available, and the market share held by these systems is increasing (39,74). Current industry trends are toward reducing CFC-11 use, while maintaining low foam density and high-resilience. Some additional examples of recent chemical developments in this area are described in Section 8 of this report.

SECTION 5

CONTROL/RECYCLE TECHNOLOGIES FOR CFC-11

A possible approach to reducing CFC-11 emissions in manufacture of flexible polyurethane foam is to apply capture/recovery or destruction systems as an add-on to the foam process. The feasibility of several alternatives has been studied in the past; most have been rejected due to technical or economic obstacles. Such systems can be categorized as follows:

- carbon adsorption with CFC-11 recovery;
- direct flame or catalytic incineration of CFC-11 in plant exhausts;
- absorption (liquid scrubbing) with CFC-11 recovery; and
- vapor condensation and recovery.

As of 1986, only carbon adsorption with CFC-11 recovery by steam regeneration has been technically evaluated to any degree. Pilot demonstrations of carbon adsorption in actual foam production facilities have had mixed success (42,44). Preliminary analysis indicates that incineration, absorption, and vapor condensation are not technically feasible. The following discussion will stress application of adsorption/recovery, although some discussion of other alternatives is warranted to point out the difficulties of applying these technologies to CFC-11 emission control.

CARBON ADSORPTION AND STEAM DESORPTION SYSTEMS

Activated carbon adsorption has been applied commercially for recovery of expensive solvents for many years. Such systems have potential for application to CFC-11 capture and recovery and have been the subject of pilot plant and engineering cost studies (13,42,44,45,46). Recent studies have begun to address technical questions, such as contamination of the carbon bed and dilution of CFC-11 in the exhaust stream. However, the economics of carbon adsorption for CFC-11 recovery are presently unfavorable, and this emission control technology has not been implemented commercially. One reason for this is the high capital expenditure required for the adsorption/regeneration/recovery hardware, as compared to the current relatively low value of the recovered CFC-11. Other disadvantages are potentially high operating costs due to fouling of the carbon adsorbent bed by isocyanate residues, and purification of the recycled CFC-11.

Process Engineering and Operating Factors

The basic physical principle applied in adsorption/recycle processes is based on the adsorptive affinity of an activated carbon surface for organic molecules, such as CFC-11. These compounds are preferentially separated from a gas stream and retained on the surface of activated carbon particles. In practice, a large volume of carbon particles are contained within a vessel, referred to as the adsorbent bed, to provide a large carbon surface area. The CFC-11 molecules are retained, or adsorbed, on the carbon and then are released, or desorbed, when the carbon particles are heated. Steam is often used to heat the carbon particles and displace the desorbed organic material. By condensing this stream, the organic material can be separated from the steam condensate (decanted), recovered, and reused.

A schematic illustrating the main features of this process appears in Figure 5-1. For a continuously regenerated system, two adsorbent bed vessels in parallel, each containing activated carbon particles, are required to

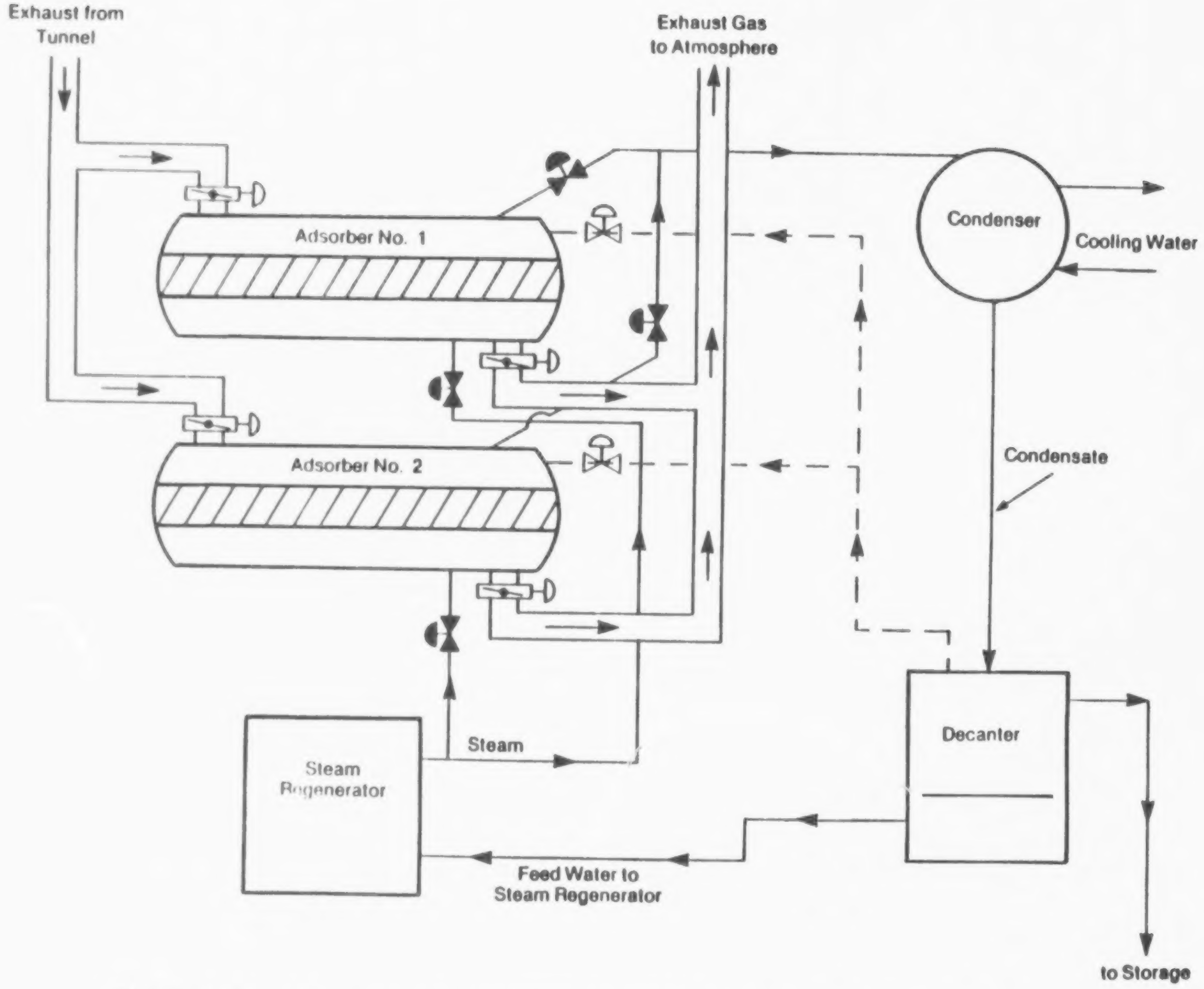

Exhaust from Tunnel
Exhaust Gas to Atmosphere
Adsorber No. 1
Adsorber No. 2
Condenser
Cooling Water
Condensate
Decanter
Steam
Steam Regenerator
Feed Water to Steam Regenerator
to Storage

Figure 5-1. Schematic flow diagram of typical carbon adsorption/solvent recycle process.

provide alternating cycles of adsorption and regeneration. A boiler and/or other heating equipment is used to provide steam and/or heated air for bed regeneration. Usually, the regeneration stream is arranged to flow countercurrent to the direction of the treated air stream (although co-current regeneration is sometimes used). A process water or chilled water condenser is included to condense the mixture of steam and CFC-11 after desorption from the carbon beds. Finally, a decanter unit separates the two phases, returning the reclaimed CFC-11 phase to the foam line CFC feed tank, or to further purification if needed.

A number of key engineering factors can be identified in applying an adsorption process to recovery of CFC-11 in flexible foam plants. The most important of these are:

- reducing the volume (flow rate) of air to be treated;
- pretreatment of the air stream to remove contaminants;
- design of an efficient regeneration/condensation unit;
- possible corrosion problems due to decomposition of the CFC;
- uniformity and quality of the reclaimed CFC-11 after many cycles; and
- costs for disposal of steam condensate and regeneration of spent carbon.

In general, the capital costs of the CFC-11 vapor collection and the carbon adsorption systems are proportional to the volume flow of air to be treated. Current ventilation practices in slabstock foam plants employ large air flows to maintain low isocyanate concentrations within the plant; this also results in dilution of the CFC-11 emissions, which is detrimental to economic recovery.

The distribution of CFC-11 emissions within the process also affects the efficiency of recovery. Emission characteristics differ widely between slabstock and molded foam processes. Table 5-1 summarizes typical emission distributions for conventional slabstock, hot molded and the HR (high resilience) molded foam processes (See Section 4 for detailed process descriptions). Slabstock lines possess the best potential for reasonable recovery efficiency because most of the blowing agent is liberated within, or not far beyond, the foam tunnel. For most existing flexible foam processes the exhaust concentration of CFC-11 is, however, relatively low. As presented previously (see Tables 4-3 and 4-5), CFC-11 concentrations in the exhaust air were less that 3000 ppm. Measurement of up to 8,000 ppm CFC-11 in the exhaust has been reported in some slabstock facilities (46). Therefore, effective design of a carbon adsorption/recovery system must also incorporate ventilation practices which reduce volume and minimize dilution of the emitted CFC-11. This must be done without resultant increases in TDI levels within the plant environment, to insure worker safety.

Proposed equipment modifications that would minimize air flow and deliver the highest possible concentration of CFC-11 to the carbon adsorber generally involve thorough enclosure, or encapsulation of the slabstock foam line to reduce the volume of ventilation air. In some existing slabstock plants, the tunnel is operated with sections of the side walls open for viewing the bun, making process adjustments, and to increase plant ventilation air flow; while in others, the tunnels are relatively well-enclosed. Therefore, the capture and dilution of CFC emissions vary from plant to plant. As discussed previously, the CFC-11 capture efficiencies measured in four representative slabstock plants ranged between 9 and 53 percent (13).

Another possible means of decreasing the total air flow to the carbon adsorbers is to cascade the dilute exhaust from one zone or collection station

TABLE 5-1. DISTRIBUTION OF CFC-11 EMISSION SOURCES IN FLEXIBLE POLYURETHANE PROCESSES

Process	Operation	Emission as Percent of Feed Auxiliary Blowing Agent
Slabstock	Mixing Head	5
	Foam Tunnel/Conveyor	50
	Bun Cut-off Saw	25
	Curing	2
	Trimming	10
	Storage	5
	Unaccounted	3
		100
Hot-Molding[a]	Raw Materials Dispensed	1
	Molds Closed	2
	Curing Oven	30
	Molds opened	9
	Product Demolded	15
	Product Crushing	15
	Post Cure	18
	Unaccounted	10
		100
HR (High Resilience)[b] Molded Process	Raw Materials Dispensed	8-10 (+5[c,d])
	Foam Rising/Cold Cure	3-5 (+5[e])
	Demolding	25
	Post Cure	40
	Crushing	15
	Product Storage	5[f]
		96-100

Notes:
[a] Emissions based on 8 weight percent CFC-11 in charge to molds.
[b] Emissions based on 7 weight percent CFC-11 in charge to molds.
[c] In addition to CFC charged to molds.
[d] Used in flushing mixing head.
[e] If oven cured.
[f] Diffusion over 10 days.

Sources: (13)

to another with a higher CFC concentration. Also, air curtains can be incorporated in the overall system to help contain emissions within the work area, and subsequently, the bulk of the air would be exhausted from below the process equipment. Such an elaborate flow scheme is not incorporated in the design and cost analysis discussed in this report, but is suggested here to indicate the potential for enhanced overall emission control.

Several design modifications can be recommended to increase the capture efficiency of CFC, while reducing the total volume of air to be handled. A greater length of the foam line could be enclosed to provide a longer residence time for release of CFC-11. Openings in the tunnel enclosure should have smallest possible cross-sectional area so that high local capture velocities can be maintained without excessive dilution of CFC-11 emissions. For example, the ends of the foam tunnel may be partially restricted to reduce air flow and yet provide for effective local CFC capture.

In most plants, there are locations adjacent to or well beyond the tunnel where high CFC-11 concentrations exist and could be enclosed to reduce dilution effects. These locations include the bun wrap paper take-off station and the bun saw area. In a previous study the conveyor line beyond the foam tunnel was also identified as a possible location of high CFC-11 concentrations (13).

An important consideration in the recovery of CFC-11 with carbon adsorption is the presence of trace contaminants in the exhaust gases. Exhaust air streams from flexible foam production will contain residual concentrations of isocyanate and amine catalyst compounds, surfactants, and entrained polyol. Both TDI and amine catalysts have been identified as contaminants which can deactivate carbon adsorbent (42,47). Once adsorbed on the carbon, TDI will react with water to form polyurea residues that coat the carbon surface and cannot be desorbed during bed regeneration. Also, trace contaminants can be carried over with the recycled CFC-11, and could adversely affect foam quality and control of sensitive formulations.

Measures to guard against contamination of the main adsorbent beds have been proposed. Injection of an alkaline water spray into the exhaust upstream of the carbon beds would promote partial reaction of isocyanate vapors to form particles that could be filtered out of the air stream (44). Possible drawbacks of this system are the increased gas-phase water content, which will compete with organics for active adsorption sites, and incomplete isocyanate removal.

Another proposed pretreatment concept is a sacrificial guard carbon bed located between the foam tunnel and the main adsorbers (13). Such a guard unit would contain a relatively small volume of carbon, and would serve to adsorb most of the trace contaminants to insure the effectiveness of the much larger main adsorber beds. The carbon in the sacrificial bed should provide ample surface area to capture TDI. Since it would not be regenerated, the sacrificial bed would remain saturated with CFC-11. Thus, the recoverable CFC-11 would be bypassed to the main adsorbent beds.

One possible guard bed configuration is shown in Figure 5-2. It consists of a thin layer of activated carbon within a separate vessel. Such a bed should be designed for low pressure drop and ease in replacing the carbon, when it becomes fouled or blinded by contaminants. A sacrificial bed of this type is included in the process engineering and cost analyses discussed in the next section.

These concerns were addressed in recent development work that has quantitatively examined the need to protect carbon adsorption beds from amine and TDI contamination. A pilot program conducted by Flakt in Denmark included measurement of irreversible carbon poisoning by TDI residues in a flexible foam production application (42). After one year of continuous pilot plant operation in conjunction with normal foam production, about 16 percent of the carbon surface, or about 5 cm of bed depth, was deactivated by urea derivatives formed by reaction of TDI with steam. On this basis, Flakt projected a three year service life for the carbon adsorbent.

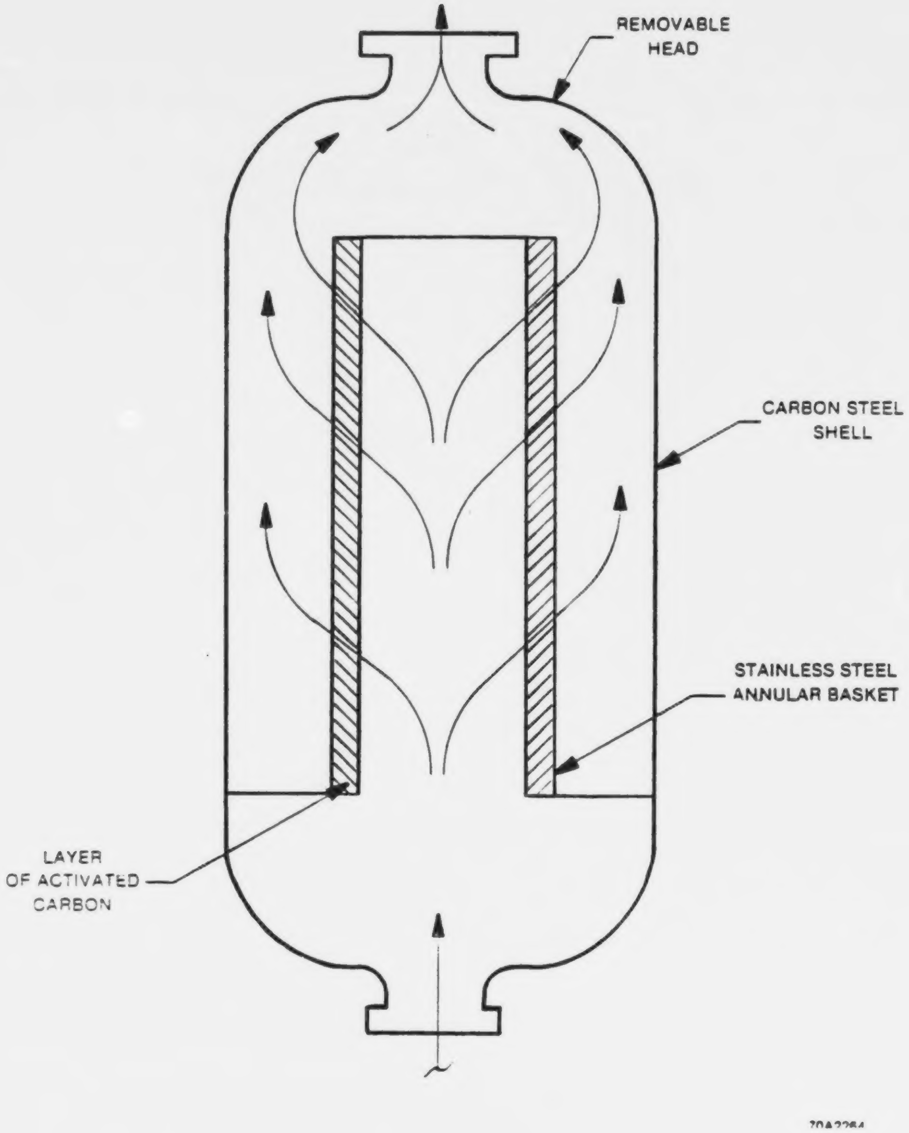

REMOVABLE HEAD
CARBON STEEL SHELL
STAINLESS STEEL ANNULAR BASKET
LAYER OF ACTIVATED CARBON
70A2264

Figure 5-2. Cross-section of proposed activated carbon guard bed for slabstock foam plant exhaust.

Loss of activated carbon capacity due to contamination by entrained amine catalyst was examined in a laboratory program described by Urano and Yamamoto (47). A simulated plant waste gas containing 2400 ppm CFC-11 and 60 ppm triethylenediamine was contacted with activated carbon through repeated adsorption/regeneration cycles. After seven cycles the carbon adsorption capacity was reduced by 23 percent. It should be noted, however, that the 60 ppm amine concentration in the waste gas was higher than would be expected in actual foam plants, for which exhaust amine concentrations have been reported to be less than 10 ppm (13). This study also demonstrated that washing of spent carbon with water removed the amine contaminant, and restored the carbon capacity to nearly its original level (47).

Regeneration of the carbon beds can be accomplished by purging with low-pressure steam. An alternative regeneration procedure would be to regenerate the beds using a heated inert gas stream (such as air or nitrogen) rather than steam. Generally, the purge steam is applied in the opposite flow direction to the CFC-laden exhaust gas. Pilot systems examined to date have used this method (42.44). Under laboratory conditions, regeneration with superheated steam at 200°C (392°F) permitted recovery of 70 to 90 percent of the adsorbed CFC-11, depending on the carbon type and particle size (47).

After steam regeneration, moisture may condense on the carbon particles. Since CFC-11 is virtually insoluble in water, it is desirable to dry the carbon bed, using dehumidified or heated air, for a period of time after steam regeneration. This feature is common to many existing full-scale solvent recovery systems, and if omitted, the bed capacity will be adversely affected.

Condensation of the desorbed CFC-11 in a water-cooled condenser is straight forward, since its condensation point is approximately room temperature, 24°C (75°F). However, it has been reported that chlorofluorocarbons can form gas phase hydrates, which would place practical restrictions on the efficiency of the condensation step (6). If this presents a problem, a hot inert gas would be a better choice for regeneration. In some facilities, it may be necessary to circulate chilled water through the condenser to improve recovery of CFC-11 from dilute regeneration streams.

Corrosion problems with CFC-11 are typically less severe than are regularly encountered in halocarbon solvent recovery systems. Although CFC-11 is relatively stable, when it comes into contact with elevated temperature surfaces, the molecules may crack, or decompose, to hydrofluoric acid (HF) and/or hydrochloric acid (HCl). If methylene chloride is also present on the carbon, then hydrolysis to form HCl can also occur during steaming. These compounds are particularly corrosive to metal duct work and the adsorber vessel. For this reason, it is generally recommended that adsorbent bed vessels be constructed of corrosion resistant materials (13,42).

The quality and uniformity of reclaimed CFC-11 is an important issue in the economic feasibility of recovery systems because of the potential operating cost credit for recovered blowing agent. In previous pilot tests of carbon adsorption/recovery, it was reported that the recovered blowing agent did not require repurification before reuse (42,44). However, there are questions remaining about the quality of recovered CFC-11 after many cycles (48). If necessary, a simple, relatively small steam distillation unit could be employed to remove impurities. Since water is used in the foam formulation a recycled blowing agent stream saturated with a predictable amount of water can be accounted for. If unknown amounts of other constituents are recycled with the CFC-11, then sensitive foam formulations could be adversely affected.

Another consideration in CFC recovery with carbon adsorption is the presence of other blowing agent vapors or solvents used to flush foam pouring equipment. Methylene chloride, for example, is used as a blowing agent and flushing solvent for the feed delivery lines and mixing head in slabstock and molded foam plants. Exhausted solvent vapors will be adsorbed in the carbon bed along with the CFC-11. If the recycled CFC-11 blowing agent contains more than a few percent of impurities, the performance of the blowing agent may be detectably altered. It may be necessary to bypass the recovery system during flushing and cleanup, or during periods of methylene chloride use.

Overall costs for carbon adsorption systems must incorporate disposal of steam condensate, and regeneration of spent carbon. If steam condensate cannot be directly discharged to the plant sewer, then some form of wastewater treatment must be practiced. Options include carbon adsorption, steam or air stripping, and direct boiler recycle. The latter may be economically preferable if a dedicated boiler is used to supply regeneration steam.

There is no reported operating experience for regeneration of carbon that has been contaminated by polyureas or amine catalyst residues. High temperature roasting should remove essentially all organics, but costs for this procedure may be prohibitive. In some localities, landfill disposal of fouled carbon may be an alternative, depending on the economics of replacement. It is expected that polyurea residues will be the more difficult contaminant to remove; laboratory experiments have demonstrated that water washing can remove amine catalyst residue (47).

Control Costs and Effectiveness

From a technical standpoint, there are two key factors that determine the effectiveness of carbon adsorption control of CFC-11 emissions at a particular facility. These are the efficiency of CFC-11 emission capture from the foam line or molded foam carousel, and the flow rate of the exhaust gas stream. Local collection efficiencies within the plant usually limit the fraction of emissions that can be controlled. Estimates of the portion of CFC-11 emissions that can be captured, assuming reasonable evolution of ventilation practices, range from 30 to 80 percent, dependent on a wide range of plant-specific parameters (13,42,44,45,46). On average, 40 to 60 percent overall reduction in emissions may be the practical limit for slabstock plants, and much smaller reductions are expected for molded foam facilities.

Consideration of the above factors indicates that slabstock foam lines offer the best application for effective control. Even with existing slabstock foam tunnel ventilation systems, CFC-11 concentrations in the exhaust air are much higher than at any point in typical molded processes. This is because CFC-11 emissions from a typical slabstock line are more localized; most of the blowing agent charge is released within, or not far beyond, the enclosed foam tunnel. Also, improvements in process enclosure are more straight forward for slabstock lines, since operator interaction can be minimized. In contrast, several operations on a molded foam carousel require participation by operating personnel. So local ventilation flows are intended to insure operator safety, and enclosure of molded foam lines is impractical. For example, manual flexing of a molded part is often needed in demolding; and this particular operation is also a major release point for CFC-11 and TDI emissions.

There is a limited experience base for carbon adsorption/recovery from which to draw conclusions concerning control effectiveness. In the pilot study described by Flakt, the original foam line ventilation system delivered a net CFC-11 recovery efficiency less than 20 percent (42) and extensive modifications to provide installation of a more concentrated exhaust increased net recovery efficiency to 40 percent. The reported recovery efficiency at an earlier pilot demonstration at a General Tire and Rubber slabstock plant was about 33 percent (44).

The cost effectiveness of an emission control method can be expressed as the dollar cost per unit CFC-11 emission averted. Control expenditures for carbon adsorption consist of the annualized capital recovery and operating costs less the credit obtained for reclaimed blowing agent. Figures 5-3 and 5-4 illustrate an analysis of control cost effectiveness based on carbon adsorption/recovery system design and operation as discussed in this section. The independent variables in the two figures are the market price for CFC-11, overall recovery efficiency, and total capital investment. This latter variable is sensitive to exhaust flow rate, ventilation design factors specific to each plant, and plant size.

In developing Figures 5-3 and 5-4, a slabstock line having 220 kg/min (450 lb/min) nominal production rate and about 13 Nm^3/s (30000 scfm) ventilation rate was examined. Operating costs were estimated on a first-half 1985

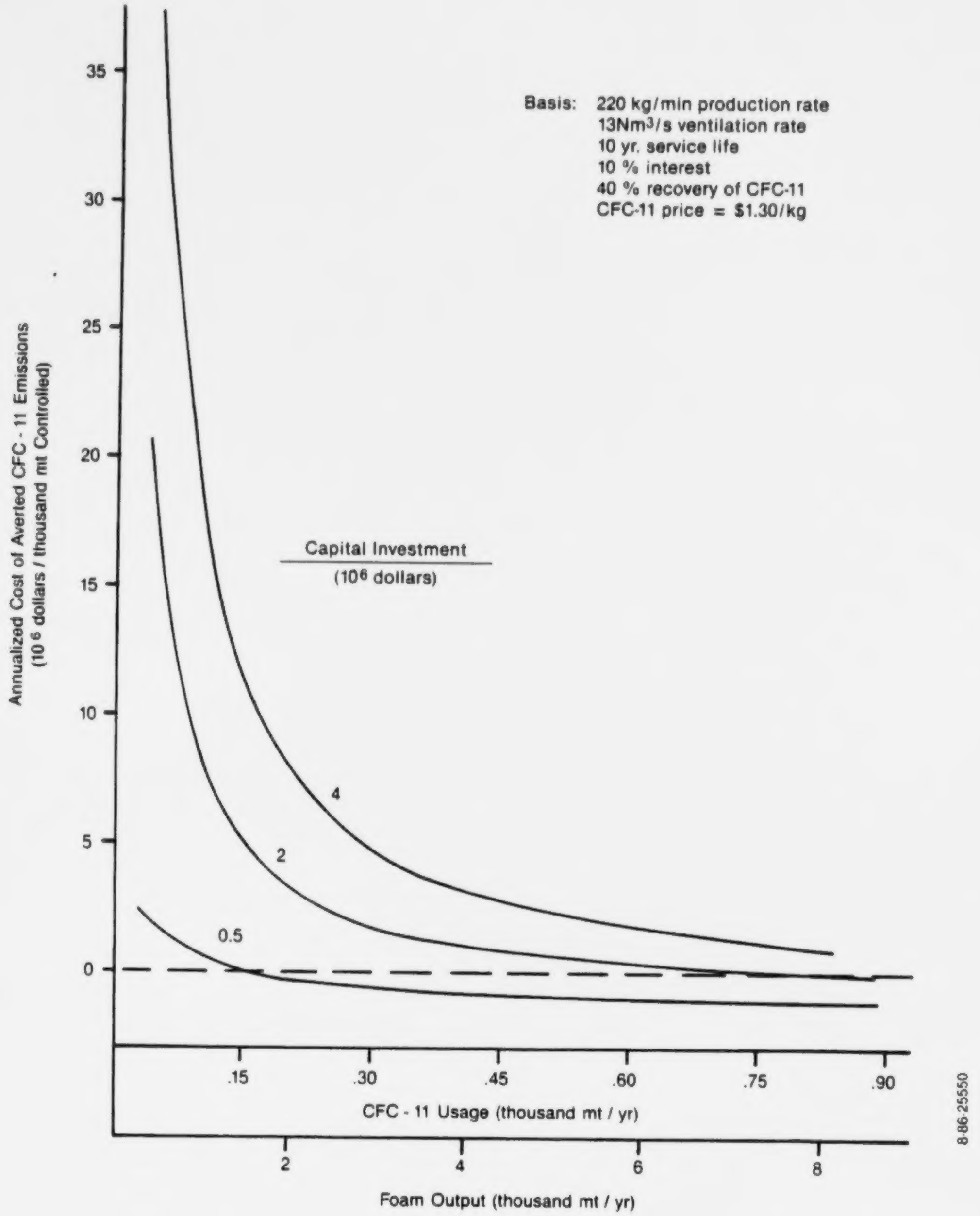


Figure 5-3. Control cost effectiveness of carbon adsorption in slabstock foam plants as a function of plant output and capital investment.

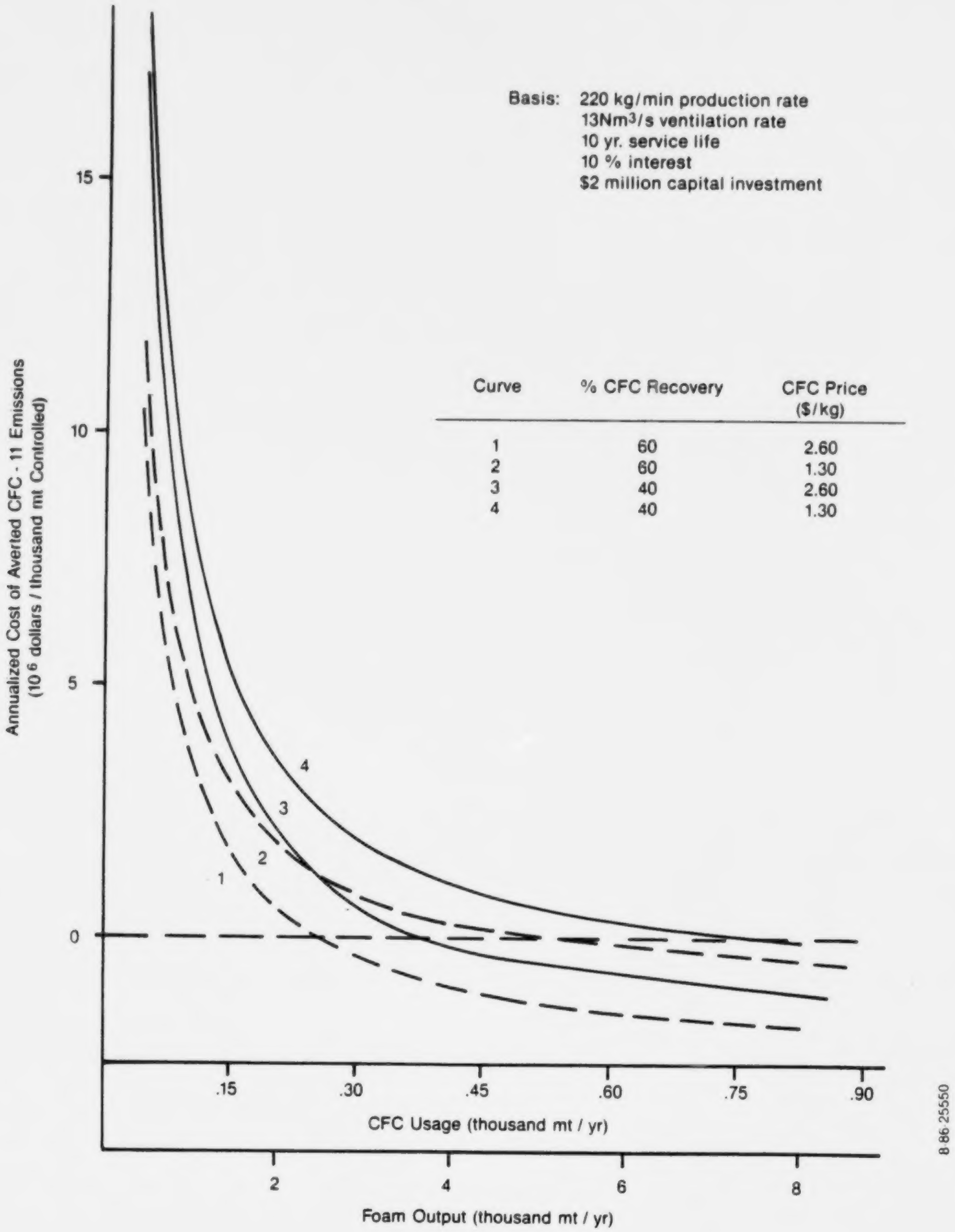


Figure 5-4. Control cost effectiveness of carbon adsorption in slabstock foam plants as a function of plant output, CFC-11 recovery efficiency, and CFC-11 price.

basis. Capital recovery was calculated for a 10 year service life, at 10 percent prevailing interest.

Inspection of the two figures reveals that control cost effectiveness is very sensitive to capital investment and foam output. Clearly, significant increases in CFC-11 price and/or recovery efficiency would provide economic incentive for implementation, and would also speed recovery of the investment. It is also apparent that optimal design of the ventilation system for high capture efficiency with minimal capital cost is advantageous. Pilot plant studies to date have not systematically defined the critical design parameters in achieving high recovery efficiency at lowest system cost.

Safety and Environmental Factors

There are no apparent adverse effects on the health and safety of workers in the flexible foam industry directly associated with use of carbon adsorption/recovery technology. In fact, this issue has not been addressed in previous studies of this control method. While the need to minimize ventilation air volume is associated with economical application of carbon adsorption control, it is crucial that the TLV for TDI (0.02 ppm) is not exceeded. Current design practice dictates sufficient air flow through the plant to provide a margin of safety with respect to TDI exposure. Care must be taken that reducing ventilated air rate to reduce carbon adsorption system costs not result in a TDI exposure hazard.

Studies to date have not addressed the impact of waste disposal associated with carbon adsorption in CFC-11 recovery applications. Wastes from the carbon adsorption process consist of contaminated, or fouled spent carbon and aqueous condensate. Isocyanate carried into the carbon beds would react with regeneration steam to form disubstituted urea compounds, which will mostly be present on the surface of the spent carbon as an insoluble residue. Process economics would probably indicate thermal regeneration and reuse of fouled carbon. Alternatively, it is possible that spent carbon could be safely disposed of by landfill, or by incineration in the process steam boilers at the foam plant. Thermal regeneration of contaminated carbon has not been tested, so it is not clear if the presence of TDI residues would preclude this procedure.

Some attention should be given to the nature of the steam condensate from these operations, since trace quantities of foam ingredients and reaction products could be present. Disposal of condensate is a consideration with all carbon adsorption solvent recovery systems that employ steam regeneration, and it may be necessary to provide wastewater treatment equipment for the condensate stream. Recycle of steam condensate from the CFC-11 separation step to the regeneration steam boiler may be feasible, although it may be advisable to include a purification step or purge stream in the recycle loop.

Activated carbon adsorbent has been shown to be very effective in reducing TDI emissions that would otherwise be released along with CFC-11. This has been noted in the pilot demonstration by Flakt, in which no TDI was detected in the effluent gas from the carbon adsorber (42). In this respect, carbon adsorption actually provides an additional benefit in reducing the total emissions of flexible foam plants.

Current Status

To date, carbon adsorption has not been applied in continuous operation at a commercial flexible foam facility. Two pilot scale studies have demonstrated the validity of the adsorption/recovery concept, but did not lead to full-scale application.

A General Tire and Rubber Company pilot study in 1968 was the first to demonstrate CFC-11 recovery from slabstock foam production (44). The results of this study indicated that the reclaimed blowing agent was of adequate quality and did not require additional purification before reuse. However, the program was discontinued on the grounds that an insufficient amount of CFC-11 was recovered to yield favorable economics. Net recovery efficiency was reported to be only 33 percent, even though the adsorption efficiency of the carbon beds was stated to be about 95 percent. However, only 30 meters (100 feet) of foam conveyor were enclosed at this plant (44).

In 1984, Flakt performed a pilot test treating a slip stream of foam line exhaust from a large slabstock plant in Denmark (42). Between 12 and 15 percent of a 18.3 Nm^3/s process exhaust stream was routed through activated carbon adsorbers. With the original ventilation arrangement at the plant, 13 to 17 percent of the CFC-11 in the treated stream was recovered, depending on the type of foam produced. Substantial modification of the foam line enclosure reduced the exhausted air flow by one-third, but net blowing agent recovery from the treated gas only increased to 20 percent. Installation of a new exhaust system which permitted withdrawal of vapors from below as well as above the foam conveyor, and adjustment of the port locations, delivered recovery efficiencies as high as 40 percent.

Another observation in the Flakt study was that the quality of the reclaimed CFC-11 was adequate for direct reuse at the host plant. Cold well-water was used to condense the regeneration stream. Although TDI residues were found to decrease the adsorption capacity of the beds, carbon life was projected to be three years based on the observed rate of deactivation. Design of an effective emission capture system was identified as the key to economical application in slabstock plants.

A laboratory study of CFC-11 adsorption/desorption phenomena on three types of activated carbon was conducted by Urano and Yamamoto (47). This work characterized the adsorption rate and capacity as a function of carbon particle size (1.0 to 2.9 mm), CFC-11 concentration (1000 to 3400 ppm), bed temperature (20 to 60°C), and gas flow rate (i.e. superficial velocity). Regeneration/desorption characteristics were evaluated at several steam temperatures (160 to 430°C) and carbon particle sizes (1.0 to 2.9 mm). It was found that an increase in particle size from 1.0 to 2.9 mm reduced the adsorption capacity by a factor of four. Capacity and adsorption rate for a given type of activated carbon was shown to be very sensitive to bed temperature, and gas flow velocity through the bed. Low gas temperatures (40°C or less) and low gas velocities are more favorable.

With respect to desorption, the same study determined for three types of carbon that a maximum of about 80 percent of the adsorbed CFC-11 could be desorbed, even with steam temperature as high as 430°C (800°F) (47). Some residual CFC, termed the "heel", is expected to remain on the carbon after regeneration. A significant drop in the fraction of CFC-11 desorbed was noted for steam temperatures less that 200°C (390°F). Particle size had only a slight effect on the fraction of CFC-11 that could be desorbed.

Development potential may exist for adsorbers consisting of carbon fiber filters, rather than conventional carbon particle beds (49). Such systems use short adsorption/regeneration cycles to recover solvents efficiently from dilute, high-volume gas streams. The carbon fiber geometry provides a large exposed surface area within a relatively small bed volume; and the rapid adsorption/desorption cycle minimizes acid formation during steam desorption, which reduces corrosion. Vacuum desorption is also more economical with these smaller volume adsorbers, making this regeneration method possible for low boiling point materials, such as CFC-11.

During 1987, a major engineering program is planned at a commercial flexible polyurethane plant in Europe (50). A full-scale carbon adsorption unit will treat exhaust from a totally encapsulated slabstock line. Factors to be examined will include optimization of CFC and isocyanate recovery, capital investment, and operating costs.

In conclusion, it appears that technical development of carbon adsorption may merit renewed efforts toward commercial demonstration. Clearly, one barrier to wide industry penetration is the very substantial capital investment. Previous studies have estimated that the capital costs for retrofit, or new plant installation, of an activated carbon system could approach or exceed the cost of the slabstock production equipment (13,42,45). Operating costs, consisting primarily of steam and electric utilities, maintenance, and condensate treatment, also represent a potential economic burden for foam producers. Additional economic considerations will be discussed in the following section.

Economic Factors

The chief economic factor in implementation of carbon adsorption for control of CFC-11 emissions from flexible foam plants is the producers' ability to recover the capital expenditure, and remain competitive. The polyurethane foam slabstock industry serves a mature and competitive commodity market in which individual producers must seek to minimize costs, even on a short term basis. For this reason, producers may find it difficult to pass along capital recovery costs.

Capital investment for carbon adsorption/recovery systems in slabstock or molded foam plants is dependent upon the ventilation air flow rate and CFC-11 concentration in the exhaust stream. These determine the required carbon bed size and fan power requirements. Additional expenses are associated with retrofit of the existing foam line ventilation system to provide for more efficient vapor capture. For representative slabstock foam plants, capital costs estimates derived in this analysis range from \$0.9 million and \$1.9 million, respectively, for 0.5 thousand mt/yr and 5 thousand mt/yr (1.1 and 11 million pound per year) facilities.

The economic disadvantages of carbon adsorption are more obvious when compared to substitution of methylene chloride for CFC-11 as a blowing agent. Although there is a tangible raw material cost advantage associated with methylene chloride use, this alternative blowing agent is not generally used to produce low density foam grades since product quality control is more difficult. On balance, conversion to methylene chloride as an auxiliary blowing agent is preferable, from the foam producer's viewpoint, to an expensive retrofit for carbon adsorption. In the absence of restrictions on methylene chloride use or emission, the conversion option would be overwhelmingly favored.

To examine these economic tradeoffs, a break-even analysis was performed to quantify the relationship between capital recovery and CFC-11 usage. Annualized operating costs and capital recovery were equated to annual raw material credit obtained from recovery of the auxiliary blowing agent.

$$\text{Annual Recovery Operating Credit for CFC-11} = \text{Capital Recovery Costs} + \text{Fixed Operating Costs} + \text{Variable Costs}$$

By deriving the recovery system operating costs on a per unit CFC-11 usage basis, it was possible to determine the capital investment for which total annualized costs equal recovery credit.

Operating and capital recovery cost estimates included in the break-even analysis represent only those associated with the carbon adsorption/recovery system. A typical production rate of 220 kg/min (450 lb/min) was assumed, and various levels of plant output were simulated by adjusting the operating period for the hypothetical foam line. This accurately reflects the situation in the flexible foam industry; plant capital costs are sensitive to the production rate, and are almost independent of total output except for the smallest plants. Operating costs were defined for a given output (based on the assumptions listed in Table 5-5), and this value was placed on a CFC-11 usage basis by assuming an average of 10.3 weight percent CFC-11 in all foam formulations. As mentioned previously, the capital recovery factor was based on 10 year service life for the equipment, and 10 percent prevailing interest.

The results of the break-even cost analysis are presented in Figures 5-5 and 5-6. The calculated direct operating cost estimates with respect to both plant output and CFC-11 usage are shown in Figure 5-5, for two levels of recovery efficiency. The largest components of these costs are system maintenance and utilities. Carbon replacement costs were not included since an acceptable payout period for the initial investment would be shorter than the service life of the activated carbon. Direct operating costs per unit CFC-11 recovered are less for larger consumers since maintenance and fixed costs become a smaller fraction of the total. Certain utility costs, such as steam

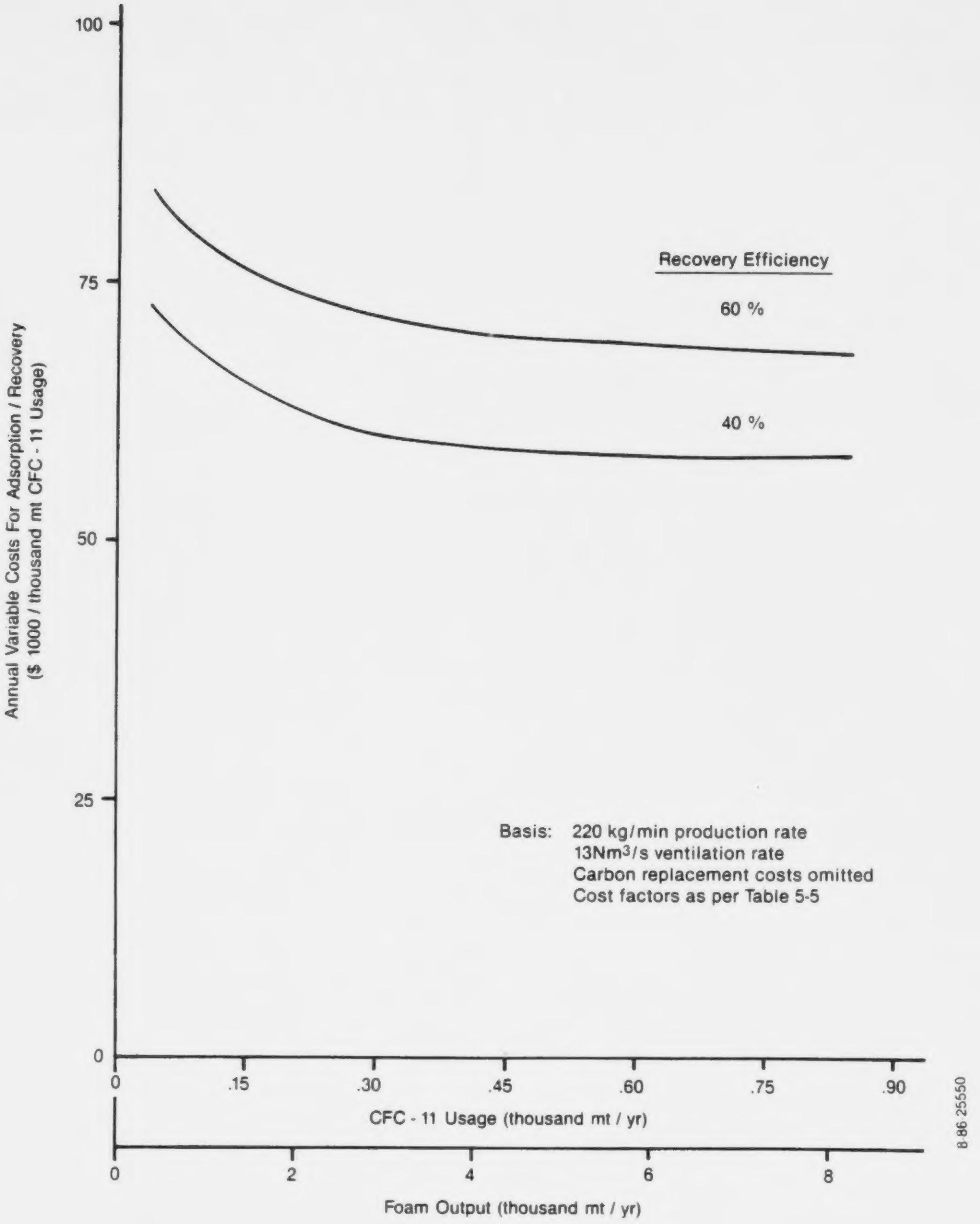


Figure 5-5. Annual variable operating cost estimates for carbon adsorption/ CFC-11 recovery in typical flexible slabstock plants.

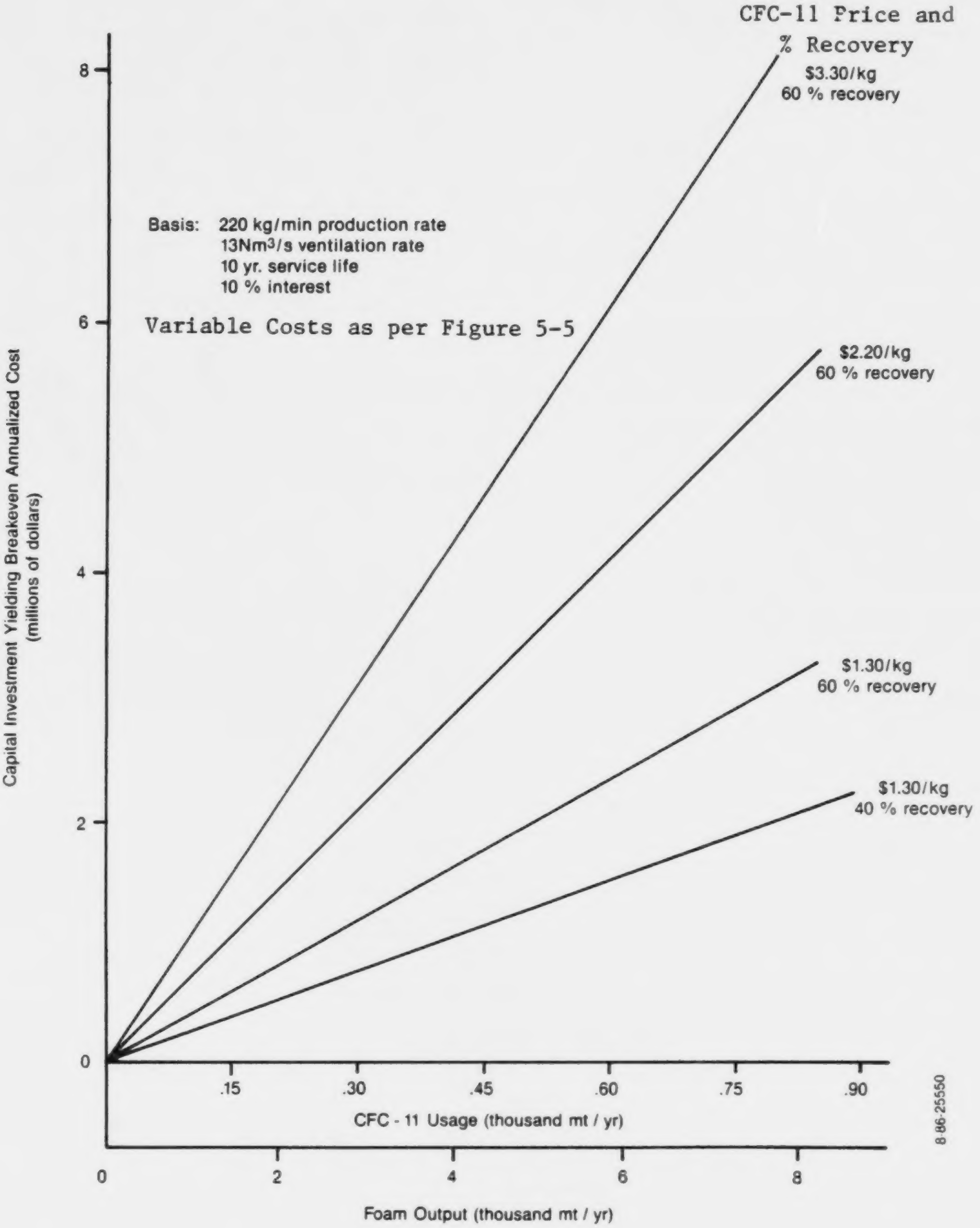


Figure 5-6. Capital investment in carbon adsorption/CFC-11 recycle system yielding breakeven annualized costs for flexible slabstock foam plants.

requirement, are roughly proportional to the amount of CFC-11 recovered; and this is reflected in the curves for differing recovery efficiencies. At all production levels, direct operating costs are relatively low compared to capital recovery costs, which are by far the largest component of the annualized costs.

As shown in Figure 5-6, plant output must exceed seven thousand metric tons per year (15.4 million lbs/yr) to obtain recovery credits equal to annualized costs on a $2 million investment, if 1985 CFC-11 prices and 40 percent recovery efficiency are assumed. Overall recovery efficiency and/or CFC-11 price must increase substantially before plants having lower output reach the break-even point. For example, with an increase in CFC-11 recovery efficiency to 60 percent at current CFC-11 prices, the break-even output for a $2 million level is reduced to about 5 thousand metric tons per year. Such improvements will require increased design efforts, and possibly increased capital and operating costs, to optimize ventilation system design and operation.

To summarize, it is clear that present ventilation design practices in the flexible foam industry, and the prevailing low price of CFC-11, result in tangible disincentives for voluntary implementation of carbon adsorption/recovery. Substantial change in this situation could arise from dramatic increase in the price of CFC-11 blowing agent, or restrictions on methylene chloride use. In general, carbon adsorption technology is well-developed and technical refinements are not likely to greatly reduce the capital expense connected with its application.

Engineering and Cost Analyses

It is anticipated that the greatest potential for economical capture and recovery of CFC-11 emissions in flexible foam plants exists at the slabstock foam conveyor line. The higher capital expenditure required to treat ventilation streams from other plant areas would not be justified, since the incremental increase in recovery would be low. Similarly, an emission capture system for molded foam facilities would probably yield very high dollar costs per unit of averted CFC-11 emission. This is because increasingly widespread use of water-blown HR (high resilience) formulations in recent years has reduced CFC consumption in molded foam plants (2,15,34). Consequently, the following analysis will examine engineering design and cost estimates for retrofit of carbon adsorption to polyurethane slabstock foam lines.

Effective design of vapor capture systems must be based on the emission profile of CFC-11 within the foam tunnel. This profile is a direct function of the original CFC charge, foam residence time in the tunnel, equipment configurations, and foam properties such as bun temperature and gelation characteristics. A typical release rate relationship is illustrated qualitatively in Figure 5-7, for a family of foam grades. Presumably, the release rate will be fastest for the most porous foams, and the total amount released will be greatest from the low density foams which require the most blowing agent.

It is apparent from Figure 5-7 that the longer the tunnel, the greater the potential recovery. Although the incremental cost of extending the tunnel or hooding may be partially offset by the value of the additional CFC-11 recovered, the cost of a larger carbon adsorption system to process the larger volume of exhaust air can be significant. Therefore, the volume of exhaust air should be reduced through the use of optimally designed foam tunnel enclosures and duct systems.

Example Plant Description--

The important parameters characterizing the example slabstock foam plant used in this engineering analysis are summarized in Table 5-2, and are representative of an average size slabstock facility. The foam machine was presumed to have two tunnel segments in sequence, one inclined followed by a horizontal section. The side paper wraps are taken off between the two sections, and these openings are enclosed and ventilated through the tunnel exhaust. Extension of the enclosure to the bun saw or curing areas is not included in this model installation.

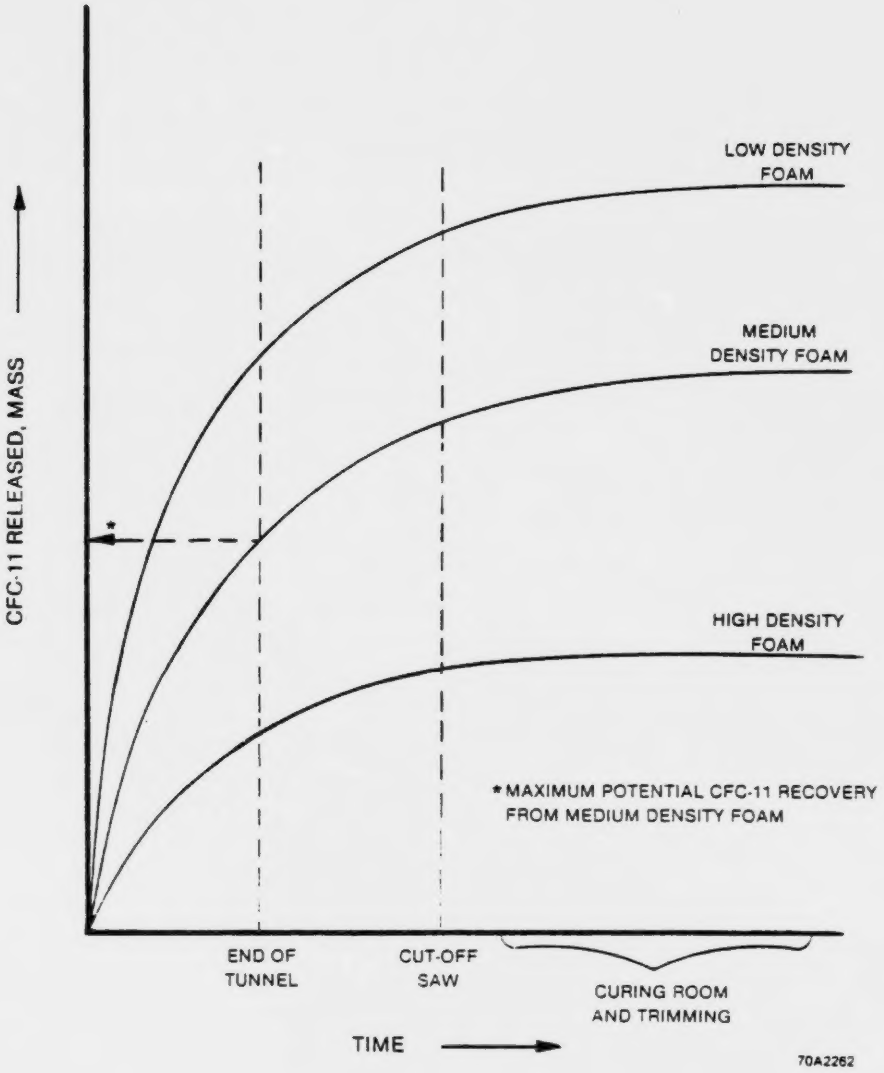


Figure 5-7. CFC-11 released from polyurethane slabstock foam as a function of time and product density.

TABLE 5-2. FLEXIBLE URETHANE FOAM SLABSTOCK MODEL PLANT PARAMETERS

Foam Machine	Continuous trough dispensing slabstock machine
Pour rate	220 kg/min (450 lb/min)
Daily foam production period	1 to 6 hours/day
Annual foam production	0.5 to 5 thousand metric tons (1 to 11 million pounds) per year
Conveyor feed	0.082 m/s (15 feet per minute)
Bun crossection	2.7 m^2 (29 ft^2)
Foam tunnel enclosure (2 sections)	Each section is 23 meters (75 feet) long, 2 meters (6 feet) high and 2.5 meters (8 feet) wide
Exhaust fan air flow	8.6 Nm^3/s (20,000 scfm) in first tunnel section; 4.3 Nm^3/s (10,000 scfm) in second tunnel section
Transfer conveyor	30.5 meters (100 feet) long to cut-off saw
Take-out conveyor	18.3 meters (60 feet) from saw to storage area
Foam storage area	2400 m^2 (26,000 ft^2)

Measurements taken during the Flakt pilot study indicated that a large portion of the released CFC-11 vapor tends to "float" near the surface of the rising bunstock. Concentration of CFC-11 close to the top foam surface averaged 50,000 ppm over the so-called "blow-off" zone, between 10 and 20 meters from the feed dispensing point (42). The key to cost-effective recovery of CFC-11 would be efficient extraction of this concentrated vapor.

Based on observations made during plant visits as part of a Radian study of slabstock production (13), vapor collection efficiencies approaching 60 or 70 percent of the released CFC-11 would be feasible with the following ventilation improvements:

- Extend foam tunnel length to provide at least 10 minutes residence time;
- Reduce open cross-sectional area at the entry and exit while keeping air velocity at 1 m/s (200 ft/min);
- Enclose side and bottom paper wrap stations;
- Provide viewing ports, access doors, etc. that would automatically remain in the closed position except when observing or testing the foam or making adjustments; and
- Relocate some vent locations to the sides of foam tunnel.

The capital cost analyses presented in this section incorporate the above modifications to the retrofitted foam line.

The model slabstock plant for this study incorporated a completely enclosed slabstock tunnel, 46 meters (150 feet) in length, corresponding to about 10 minutes residence time. It was assumed this would allow about 70 percent of the original charge of CFC-11 to be released within the tunnel. This agrees with previous measurements by Flakt (42). It was further assumed that about 85 percent of the released auxiliary blowing agent would be captured in the tunnel exhaust system. Therefore, the net exhaust capture efficiency was estimated to be 60 percent of the initial CFC-11 charge for the design conditions based on supersoft foam production. This may appear to be optimistic, given the measured capture efficiencies summarized in Table 4-4, and the 40 percent recovery noted by Flakt (42). However, this recovery is a reasonable extrapolation of existing plant data, if optimal design of the tunnel enclosure is emphasized.

For this example, the carbon beds were designed for the highest expected CFC-11 pouring rate. For production of a supersoft foam with density of 16 kg/m^3 ($1\ lb/ft^3$), the CFC-11 blowing agent typically accounts for about 13 percent of the foam formulation. Based on the model slabstock line pouring rate of 220 kg/min (490 lb/min) of foam, this corresponds to a CFC-11 pouring rate of 28.6 kg/min (63 lb/min). For the assumed vapor capture efficiency of 60 percent, the carbon adsorbers for the example plant were sized for recovery of 16.3 kg/min (36 lb/min) of CFC-11. Activated carbon adsorption beds can be designed to adsorb at least 95 percent of the CFC-11 in the exhaust air stream. Combining this factor with the assumed capture efficiency, the overall net recovery potential for the system design conditions is about 57 percent of the CFC-11 contained in the foam feed.

While the design condition recovery rate provided the basis for carbon bed sizing, the average CFC-11 recovery rate over all foam grades would be lower, and the operating cycle of the adsorption system could be adjusted accordingly. Table 5-3 summarizes the major design parameters for the example recovery system.

Figure 5-8 depicts the proposed carbon adsorption/recovery system for CFC-11. Three beds in parallel would be required for 5-8 hour/day operation at the design throughput; two operating simultaneously in adsorption mode, with the third being regenerated. Alternatively, one or two bed systems may be adequate for shorter slabstock line operating periods.

TABLE 5-3. DESIGN PARAMETERS FOR CARBON ADSORPTION SYSTEM IN MODEL SLABSTOCK PLANT

Foam Tunnel Exhaust Parameters		
Pour Rate	220 kg/min	Base case, typical
CFC Pour Rate	28.6 kg/min	13.0 wt. % CFC formulation for 16kg/m^3 (1.0 lb/ft^3)
Tunnel Length	46 m	Assumed, typical
Time in Tunnel	10 minutes	Assumed
CFC Release Rate in Tunnel	20.0 kg/min	Calculated as 70% of CFC pour rate
CFC Capture Efficiency	60%	Based on CFC pour rate
Exhaust Air Rate	13 Nm^3/S	Assumed, typical for base case pour rate
CFC Concentration	0.026 kg/Nm^3 5000 ppmv	Calculated from CFC release rate and exhaust flow
Carbon Adsorption System Parameters		
Carbon Bed Efficiency	95%	Reasonable for activated carbon beds
CFC Recovered	16.3 kg/min	CFC pour rate x 0.6 x 0.95
Overall Recovery Efficiency at Design Conditions	57%	Based on CFC pour rate
Operating Capacity of Carbon	0.10 kg CFC/kg Carbon	50% of capacity at 0.48 kN/m^2 (0.7 psia) and 37.8°C (100°F) from Figure 5-9

(Continued)

TABLE 5-3 (Continued)

Carbon Required per Bed	9,800 kg	For one hour saturation time
Bed Volume	20.4 m^3	Based on 490 kg/m^3 carbon packing density
Bed Area	19 m^2	Based on 0.38 m/s (75 ft./min.) gas velocity
Total Carbon Required	29,400 kg	For a 3-bed system
Instantaneous Steam Rate	4500 kg/hr	Calc'd for one-hour bed regeneration cycle
Cooling Water Requirement	2.6 m^3/min	Condenser water available for 120% of operating period

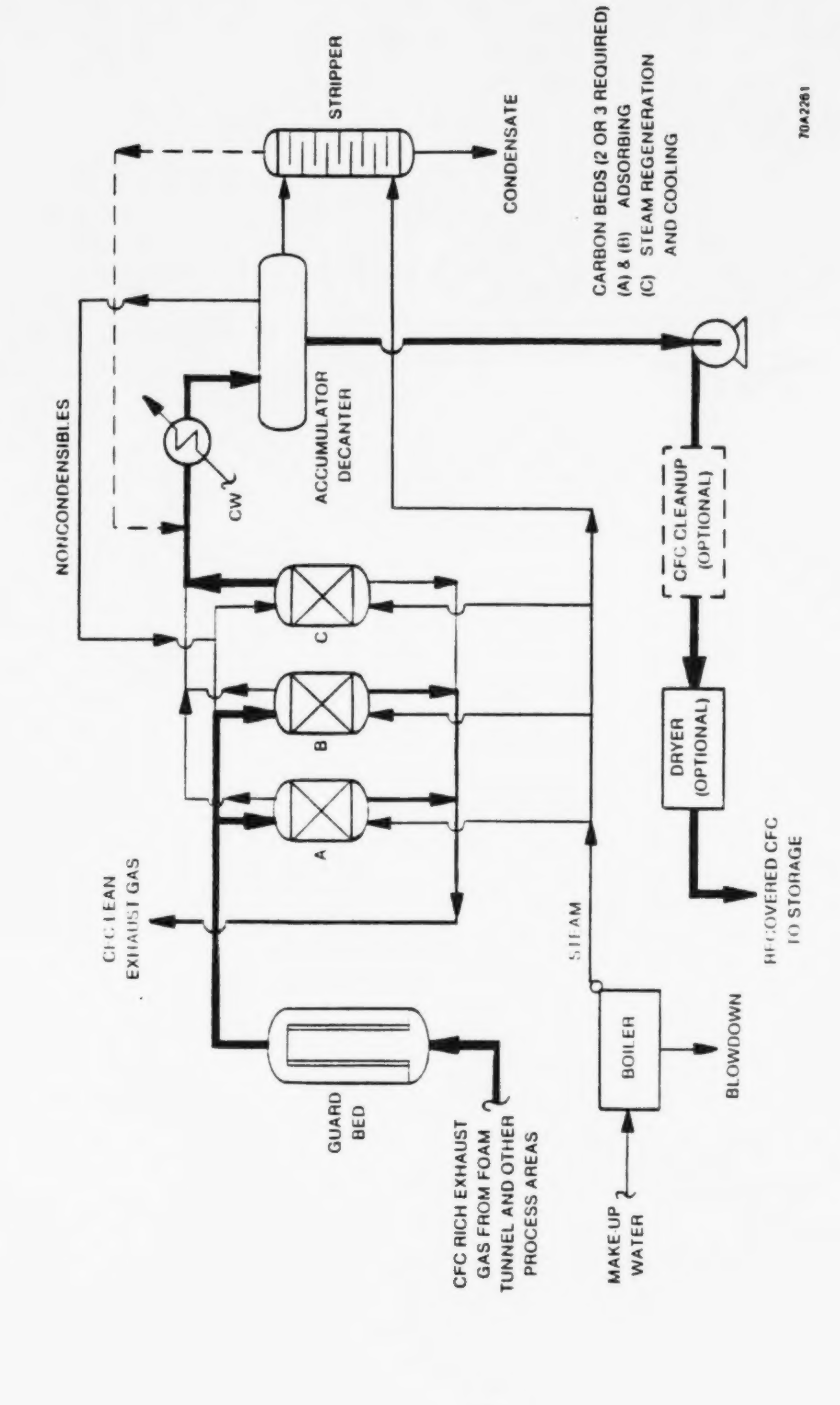

CFC RICH EXHAUST GAS FROM FOAM TUNNEL AND OTHER PROCESS AREAS
GUARD BED
CFC LEAN EXHAUST GAS
A
B
C
NONCONDENSIBLES
CW
ACCUMULATOR DECANTER
STRIPPER
CONDENSATE
MAKE-UP WATER
BOILER
BLOWDOWN
STEAM
CFC CLEANUP (OPTIONAL)
DRYER (OPTIONAL)
RECOVERED CFC TO STORAGE
CARBON BEDS (2 OR 3 REQUIRED)
(A) & (B) ADSORBING
(C) STEAM REGENERATION AND COOLING
70A2261

Figure 5-8. Schematic flow diagram of carbon adsorption system for CFC-11 recovery in slabstock foam plants.

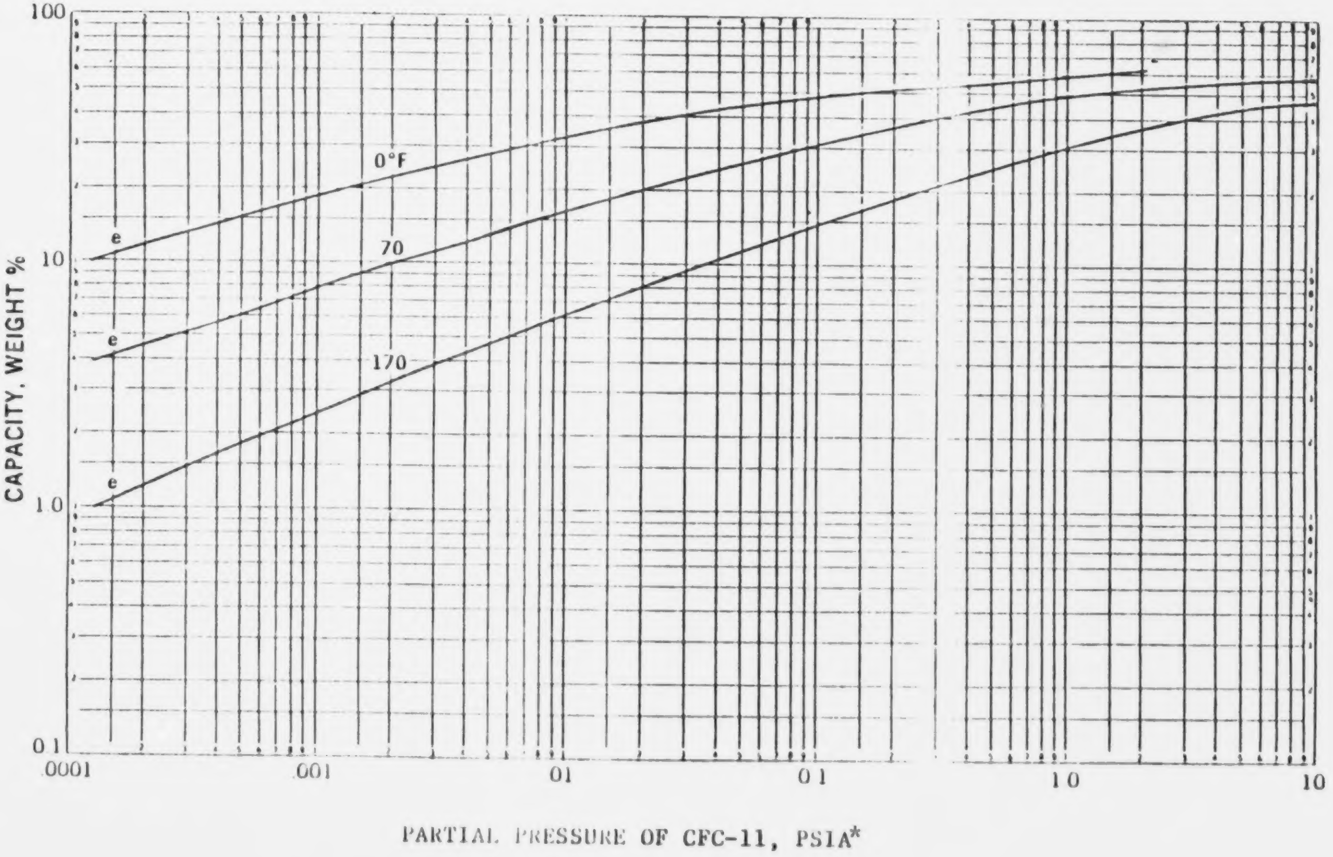
As discussed previously, it is necessary to avoid contamination of the main adsorbent beds by entrained TDI and/or amine catalyst vapors. To accomplish this, a guard carbon bed (see Figure 5-2 for details) is located upstream of the main adsorbers.

Steam for desorption and bed regeneration is provided by a dedicated boiler unit. The regeneration stream is routed counter-currently to the direction of treated air flow, for more efficient desorption, and then through a water-cooled condenser. The condensible components in the desorption effluent are separated in an accumulator/decanter vessel. Additional components for this control process may include a simple distillation step to purify the reclaimed blowing agent, and provision to dry the carbon beds following regeneration.

Carbon Bed Design--

Based on the performance of carbon adsorption systems in other service, efficiencies of recovery in excess of 95 percent can be attained. Adsorption capacity for a given activated carbon as a function of temperature and gas stream concentration can be determined from experimentally derived relationships referred to as isotherms. Isotherms for Calgon BPL® activated carbon used in the example system appear in Figure 5-9; similar data for other types of activated carbon are available from vendors of carbon adsorption systems.

Using the available isotherm data, a realistic design basis can be derived for CFC-11 adsorption beds. For the example system, the removal rate of CFC-11 from the air stream is 16.3 kg/min (36 lb/min) and the exhaust air flow is 13 Nm^3/s (30,000 scfm), which is assumed to enter the bed at about 37.8°C (100°F). At an assumed average concentration of 5000 ppm, and CFC-11 partial pressure of 0.48 kN/m^2 (0.07 psia) based on a bed temperature of 37.8°C (100°F). For these conditions, the BPL carbon adsorption capacity can be estimated to be about 20 weight percent from Figure 5-9. An appropriate design rule is that the working bed capacity is one half of this value, or 10 weight percent. This allows for residual CFC-11 remaining in the bed after each regeneration cycle, (i.e., the CFC heel) and for the loss of carbon



* 1 psia = 6895N/m^2

Figure 5-9. CFC-11 adsorption isotherm on BPL activated carbon.

Source: Calgon Corporation, Pittsburgh, PA capacity due to contamination. Typically, packed carbon particles have a density of 490 kg/m^3 (30 lb/ft^3); therefore, each cubic meter of bed volume will adsorb 49 kg of CFC-11 (3 lb CFC-11/ft^3).

This bed design basis is consistent with previous measurements. Exhaust duct concentrations in the Flakt pilot study ranged from 3,000 to nearly 10,000 ppm along the enclosed slab line when recovery was about 40%. Also, the design bed working capacity for that study was taken as 15 to 20 weight percent CFC-11 (42).

To provide the required continuous capacity without excessive bed size, the system includes three carbon beds in parallel, two beds being on-line (adsorbing) with the remaining bed being regenerated. Beds of the size anticipated for this service require about one hour for steaming and cooling, so each bed was assumed to remain off-line for two hours per daily cycle.

For air flows in the range of 13 Nm^3/s (30,000 scfm), carbon adsorption beds are usually loaded in large horizontal steel tanks, at a depth of about 0.6 to 1.8 meters (2 to 6 feet). To achieve 95 percent recovery in the bed, a reasonable maximum gas velocity is 0.51 meters/sec (100 fpm). Also, since the cost of operating the exhaust fans is dependent on the pressure drop across the beds, a shallow bed is preferred. Therefore, a bed cross-section of 19 m^2 (200 ft^2) was selected for the example design. This results in a bed depth of about one meter, and the superficial gas velocity would be approximately 0.38 meters/sec (75 fpm).

Since the expected recovery rate is 16.3 kg/min (36 lb/min), each bed is sized to adsorb 980 kg (2160 lbs.) of CFC-11 during each on-line period. This requires about 9,800 kg of carbon per bed, which would occupy a volume of 20.4 m^3 (720 ft^3). For three beds the total quantity of activated carbon purchased would be 29,400 kg (64,800 lbs.)

Carbon Bed Regeneration and CFC Recycle--

To desorb the CFC-11, and regenerate the carbon beds, three options are available. One is to circulate a hot, inert gas through the bed to supply the heat of desorption. Second, the hot inert gas can be combined with a reduced pressure atmosphere in the adsorber, created by a vacuum pump, to obtain higher recovery efficiencies. Finally, the procedure used more often, and that selected for this example, is to flow superheated, low-pressure steam upward through the bed counter-current to the flow of CFC-laden exhaust gases during adsorption, to strip off the CFC-11. The CFC-11 rich steam is then routed to a water-cooled heat exchanger to condense the steam and the CFC-11. The aqueous condensate is decanted from the liquid CFC-11, and may be treated, if necessary, to remove residual organics prior to discharge or recycle.

The steam required to regenerate the beds was estimated to be 2,940 kg (6,480 lbs) per cycle, based on a typical factor of 0.3 kg steam per kg of carbon. Steam will flow through the bed for three-fourths of the regeneration period, or 45 minutes, so the instantaneous steam rate would be 3,920 kg/hr (8,640 lb/hr). Therefore, a boiler capacity of at least 4,500 kg/hr (10,000 lb/hr) is required for a 3-bed system as indicated in Table 5-3; proportionately smaller boiler capacities are applied for 1 and 2-bed systems.

Previous pilot plant demonstrations have shown that the reclaimed CFC-11 did not require additional purification downstream of the decanting step (42,44). If necessary, a simple steam distillation column and condenser could be used to remove heavier organics from the decanted blowing agent prior to reuse. A purification sub-system of this type is incorporated into the example plant system. No special drying is anticipated other than removing entrained water by means of a simple cartridge type coalescer. Since water is always included in the foam formulation, use of water-saturated CFC-11 should not normally be a problem, as long as the water content is predictable.

Capital Costs--

The adsorption/recovery hardware required for most existing slabstock plants would be similar, since pouring and ventilation rates that determine equipment requirements are similar. Thus the estimated capital cost of retrofitting an existing polyurethane slabstock foam plant is essentially independent of the plant's production level above about 2 thousand metric tons per year (4.5 million pounds/yr). Below that level, capital costs are reduced by 25 percent if two-bed carbon adsorption system is required and 50 percent for small facilities using only one carbon bed. This corresponds to plants that do not operate the foam line more than an average of two hours per day.

Total capital cost estimates for a retrofit carbon adsorption/recovery system for CFC-11 are presented in Table 5-4. These figures were developed by applying generally accepted installation and indirect cost factors to the total purchased equipment costs (13,51). The total capital investment for a large 3-bed adsorption/recovery system was estimated at $1.9 million, while 2 and 1-bed systems cost $1.4 and $0.9 million, respectively. These costs are based on first-half 1985 dollars and are assumed accurate within 30 percent. Direct installation and capital equipment costs account for over 50 percent of these totals. The largest components of the purchased equipment costs are the carbon adsorber beds and associated process equipment, and the CFC-11 purification system. This latter item may not be required for all plants.

The capital costs for retrofit installations can be expected to vary significantly, due to different plant configurations. The rate of new plant construction is slow, so it is anticipated that retrofit application would be the primary means of implementing this CFC-11 control.

Annualized Operating Costs and Cost Effectiveness--

Annualized costs for operating a CFC-11 recovery system were developed for three levels of production: 0.5, 2, and 5 thousand metric tons (1.1, 4.4, and 11 million pounds) per year. These costs, and the bases used, are summarized in Table 5-5. In general, the annualized costs depend on the volume of foam produced, which sets the direct operating expenditures, and the capital investment, which establishes the level of capital recovery costs.

TABLE 5-4. CARBON ADSORPTION SYSTEM CAPITAL COST ESTIMATE FOR SLABSTOCK FOAM PLANTS

	Number of Carbon Beds		
Flowrate, 13 Nm^3/S (30000 cfm)	3	2	1
Direct Capital	(Cost in $1000, Mid-1985)		
Carbon Beds (316SS) with instruments controls, valves, fans, condensers, decanter	436	320	210
Boiler, 4500 kg/hr 10,000 lb/hr) for 3 beds 2250 kg/hr (5,000 lb/hr) for 2 beds 1270 kg/hr (2,800 lb/hr) for 1 bed	44	28	23
Guard Bed	24	24[a]	0
Revamped Enclosure[b]	17	17	17
Ductwork[b]	18	18	18
Recycle CFC Pump, Dryer, Storage	9	9	7
Cooling Tower, Pump/Meter	40	20	10
CFC-11 Purification system[c]	140	110	72
TOTAL PURCHASED EQUIPMENT COST	728	546	357
TOTAL INSTALLED DIRECT COST[d]	1201	900	590
Indirect Capital (% of Direct Capital)			
Engineering and supervision at 10%	120	90	60
Misc. field construction expenses at 5%	60	45	30
Contractor fees at 10%	120	90	60
Contingencies at 20%	240	180	120
Startup expenses at 2%	24	18	12
Interest during construction at 10%[e]	120	90	60
TOTAL INDIRECT CAPITAL	684	513	342
TOTAL DEPRECIABLE CAPITAL (TDC + TIC)	1885	1413	932
Working capital[f]	6	3	2
TOTAL CAPITAL INVESTMENT (TCI)	1891	1416	934
(ROUND-OFF)	1900	1420	930

[a] This item may be omitted for plants with a very low production rate.

[b] These costs are sensitive to specific site.

[c] Distillation system with 24 hour storage assumed (if necessary).

[d] All installation direct costs equal to 65 percent of purchased equipment cost (13).

[e] 10% per year with one year construction period assumed.

[f] At 25% of annual direct operating and maintenance costs (Table 5-5).

TABLE 5-5. ANNUALIZED COST ESTIMATES FOR CFC-11 RECOVERY SYSTEM AT SLABSTOCK FOAM PLANTS (MID-1985 DOLLARS)

		$ 930,000 (1-bed)		
Cost Basis		$1,420,000 (2-beds)		
Total Capital Investment (TCI):		$1,900,000 (3-beds)		
Annual Production thousand mt (million lbs):		0.5 (1.1)	2.0 (4.4)	5 (11)
Number of Carbon Beds		1	2	3
Operating Days		50	100	165
Hours/Day		1	3	5
Direct Operating and Maintenance Costs	Rates			
Operating Labor[a]	$13/hr	0.4	0.8	1.1
Maintenance[b]		20.0	42.6	60.0
Electricity[c]	$0.043/kwh	0.7	1.8	3.9
Steam[d]	$18.5/1000 kg/hr ($8.40/1000 lb/hr)	5.4	21.4	67.0
Process and Cooling water[e]	$0.066/$m^3$ ($0.25/1000 gal)	1.3	4.0	8.6
TOTAL DIRECT COSTS		27.8	70.6	140.6
Indirect Costs				
		152.0	231.1	309.0
Capital recovery factor[f]		8.2	17.4	24.4
Overheads[g]		5.2	11.1	15.6
Administration[h]		18.6	28.4	38.0
Insurance and Property Taxes[i]		157	288	387
TOTAL INDIRECT COSTS		185	359	527
TOTAL ANNUALIZED OPERATING AND MAINTENANCE EXPENSES (ROUND-OFF)		185	360	530

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[a] 0.5 hr/day operating labor and supervision at 15 percent of labor.

[b] Includes maintenance labor, materials, and supervision and is estimated at 3 percent of the direct capital costs.

[c] 15.5 kw/Nm^3/sec (5 hp/1000 cfm), operating 120 percent of daily period.

[d] Bed regeneration: 4,500 kg/hr capacity, 0.3 kg steam/kg carbon; CFC-11 purification system: 28 kg steam/kmole CFC-11 (51).

[e] 2.6 m^3/min (700 gpm), operating 120 percent of daily period.

[f] Estimated at 16.275 percent of the total capital investment.

[g] Estimated at 40 percent of labor expenses.

[h] Estimated at 50 percent of the operating labor and 25 percent of the maintenance.

[i] Estimated at 2 percent of the total capital investment.

The various categories of direct and indirect operating expenses associated with the carbon adsorption/recovery system were estimated in terms of first-half 1985 dollars. Maintenance costs and steam consumption are the largest direct operating cost items, and both of these costs increase with foam output. Capital recovery, calculated for 10 year service life and 10 percent interest, is by far the largest fixed cost item, accounting for 60 to 80 percent of the total annualized costs. By comparison, direct operating costs are relatively low.

Also to be considered in evaluations of net operating costs and cost effectiveness is the credit for reclaimed blowing agent. The value of CFC-11 recovered may vary by as much as a factor of 100 among existing slabstock facilities. This variation is a consequence of several of the following factors:

- differences in foam output level;
- variations in the distribution of foam grades produced. CFC-11 usage typically ranges between 4 and 16 weight percent of the feed material for different density products; and
- the capture efficiency of CFC-11 vapors emitted within the plant which may range from 10 to 70 percent, depending on the arrangement and design of the exhaust system.

To calculate the recovery credit, it was assumed that a representative distribution of products would have an average density of 21 kg/m^3 (1.3 lb/ft^3), and that the average CFC-11 usage equal 10.3 weight percent of the total foam production. The average recovery efficiency over all production conditions would be slightly less than that assumed for adsorption system design conditions. For this reason, overall recovery efficiency for calculation of control cost-effectiveness has been estimated to be 50 percent of total usage, for an optimally designed recovery system.

The control cost effectiveness of a retrofitted capture and recovery system for CFC-11 can be expressed as the cost per unit weight of CFC-11 recovered, or alternatively, as the cost per unit of CFC-11 emission averted. The cost effectiveness of a recovery system for a slabstock plant is not only a function of the efficiency of the control system itself, but is very dependent on the mass flow of CFC-11. This in turn is proportional to the production rate, and inversely proportional to the average product density for a given facility.

Table 5-6 presents a summary of cost effectiveness for the three plant sizes discussed above. The cost per unit of CFC-11 emission averted is inversely proportional to, and strongly dependent on, CFC-11 usage. As would be expected, there is a significant improvement in retrofit economics as plant size increases. This is mostly a result of the larger quantity of CFC-11 recovered per dollar of capital expense. Based on current market price for CFC-11, $1.30/kg ($0.60/lb), flexible foam plants with output in excess of 6 thousand mt/yr (12.5 million lbs/yr) could recover their annualized costs through blowing agent cost savings alone assuming the recovered CFC-11 could be reused for many cycles. Raw material cost credits for such facilities could amount to more than $350 thousand per year.

Barriers to Implementation and Time Frame

There are some remaining technical issues which should be resolved before widespread implementation of carbon adsorption can be recommended. Among these issues are appropriate ventilation design/modification criteria, disposal of secondary by-product streams (condensate and spent carbon), and the effect of contaminants on recovered blowing agent. Thorough pilot tests and commercial scale demonstrations should be conducted to address these questions. In addition to these technical obstacles, a major economic barrier to implementation is the high capital expense associated with retrofit of suitable systems to existing foam plants. In light of these difficulties, the analysis presented above could be considered optimistic, since it presumes favorable resolution of remaining technical problems.

TABLE 5-6. ESTIMATED COST EFFECTIVENESS OF CFC-11 RECOVERY SYSTEM AT SLABSTOCK FOAM PLANTS

Annual Foam Production, Thousand mt/yr	0.5	2	5
CFC-11 Usage[a], thousand mt/yr	0.051	0.21	0.51
CFC-11 Recovered[b], thousand mt/yr	0.026	0.11	0.26
Annualized Costs of Recovery System[c], $1000/yr	185	360	530
Revenue from Reclaimed CFC-11[d], $1,000/yr	34	143	338
Net Cost (Profit) of Recovery System Operation, $1000/yr	151	217	192
Cost Effectiveness, $1000/mt CFC-11 recovered	5.8	2.0	0.7

[a] Assumes total foam production uses on average .103 kg CFC-11/kg foam.
[b] Estimated 50% overall recovery efficiency.
[c] From Table 5-5.
[d] Mid-1985 CFC-11 price = $1.30/kg (0.59/lb.)

The cost per unit of CFC-11 emission averted by this control method would be much higher for molded flexible foam facilities. For these processes the prompt emissions of blowing agent released during foam formation are spread throughout the process and cannot be practically contained. This is in contrast to the slabstock foam tunnel, in which a large portion of blowing agent emissions are more localized. The blowing agent emitted from existing molded foam carousels also tends to be greatly diluted with a greater amount of ventilation air drawn in from the plant surroundings.

It would be anticipated that the capital costs to install enclosures for a molded foam carousel would be prohibitive. There is also an important technical limitation, in that several of the process steps, as described in Section 4 require direct access to the molds by plant personnel, which would complicate, or render impossible, effective enclosure.

An appropriate time frame for implementing this control technique would depend on the economic incentive for plant retrofits. One way to effect implementation would be to cause the market price for CFC-11 to increase markedly, thus increasing the raw material credit for recovery, and penalizing firms for continued purchase of fresh material. Conversion to methylene chloride blowing agent might be the preferred option for most smaller producers. It is doubtful that widespread implementation of carbon adsorption control technology would occur in the absence of restrictions on methylene chloride use. Over the longer term, substitution of CFC compounds having ozone depletion potential lower than CFC-11 (discussed in Section 6) may be preferable to capital-intensive recovery systems.

Presuming that economic barriers could be made less prohibitive, it should be possible to retrofit and bring control systems on-line for larger slabstock facilities within five to seven years. This includes some time for experimental evaluation of important design and environmental factors, as well as additional pilot scale and full scale demonstrations. If carbon adsorption were to emerge as a preferred CFC control option for all flexible foam facilities, molded foam producers might opt instead for production of more dense water-blown foam systems, thus reducing the availability of low-density molded foam.

It is also possible that the realignment in the foam industry caused by the high cost of controlling blowing agent emissions will stimulate research investment. Such efforts could result in the introduction of new cushioning products, innovative foaming processes, and/or alternative blowing agents. Some potential foam processes and substitute chemicals that would fulfill this role are discussed in following sections of this report.

INCINERATION OF PLANT EXHAUST

Destruction of chlorofluorocarbon emissions by thermal or catalytic incineration is physically possible. However, several crucial problems can be identified that prevent its consideration as a technically practical emission control method. Since CFC-11 is nonflammable, high incineration temperatures are necessary to cause thermal cracking. Also, a large volume of exhaust air must be treated to effectively control blowing agent emissions. This results in an excessively large energy cost.

In general, nonflammable CFC compounds are not easily destroyed through conventional incineration techniques. Although CFC-11 decomposes above 540°C (1000°F), this is only true in a reducing atmosphere, such as a fuel-rich flame. The resulting gases contain hydrochloric (HCl) and hydrofluoric (HF) acids. These are secondary pollutants which are highly corrosive, and would have to be scrubbed from the flame exhaust. Tests by DuPont indicated that such fuel-rich flames can destroy over 99 percent of the chlorofluorocarbons present in typical process streams (13). It is also not known what effect the incineration products of entrained isocyanate and polyol would have on emissions.

Catalytic incineration mechanisms include disproportionation of CFC-11 in the presence of aluminum chloride ($AlCl_3$) to form carbon tetrachloride (CCl_4) and carbon tetrafluoride (CF_4). This is a relatively exotic and expensive process. Under oxygen-free conditions, finely divided metallic iron at very high temperatures will react with chlorofluorocarbons to form metal halides (13). Aside from the extremely high energy costs, this latter process would require expensive treatment of the high-volume exhaust to remove oxygen.

It is possible to thermally crack CFC-11 at temperatures above 760°C (1400°F), but there are no published data which characterize the residual products of the cracking reactions. Likely combustion products are corrosive hydrogen fluoride and hydrogen chloride gases, which would necessitate expensive materials of construction. This process would require large kiln-like equipment to treat most or all of the exhaust stream. A proposed alternative to direct flame incineration would be the use of a heated sand bed or fluidized bed. No tests of such a process for CFC destruction have been reported.

Each of these proposed incineration destruction techniques involve energy-intensive processing of large volumes of exhaust air. While these methods may very effectively destroy CFC-11, the costs would be extremely prohibitive. Operating costs alone for a 13 Nm^3/s (30,000 scfm) exhaust system could be expected to exceed $10 million per year (51). Most or all of the input energy for thermal processes would be wasted, since the flexible foam production process could not utilize the waste heat. Because of the preponderance of negative factors, incineration techniques were not pursued further in this study.

CONCENTRATION AND/OR CONDENSATION PROCESSES

Liquid Absorption

An infrequently applied technology for organic solvent recovery from air steams is liquid absorption. This process usually employs a packed or tray type column for gas/liquid contacting, followed by degassing of the scrubbing solvent using heat or reduced pressure. Since the CFC-11 is relatively dilute in large-volume exhaust air streams, the required scrubbing columns would be large. Another potential problem could be the replacement of CFC-11 emissions with releases of organic scrubbing solvent in the exiting air.

Petroleum based oils have been proposed for a scrubbing solvent (52). It was pointed out that an exiting air stream at 38°C (100°F), which is typical for slabstock exhaust, would contain about 100 ppm of oil vapor. In addition, progressive oxidation of mineral oils would contribute a significant odor problem. Special vacuum distilled and carefully refined oils are available that have exceedingly low vapor pressure, and other low volatility organic solvents such as nonvolatile plasticizers could be used. However, the high cost of such absorbents would argue against their use.

Other scrubbing solvents may be feasible for scrubbing CFC-11 emissions. For example, CFC-11 is soluble in most alcohols (53). It is possible that scrubbing solutions of one or more alcohols could be developed that would have appropriate solvent and volatility properties. A simple water wash of the air leaving the main scrubber could then be used to prevent solvent emissions. Additional investigation in this area could improve the outlook for liquid scrubbing for CFC-11 controls.

A liquid scrubbing system could provide a raw material cost credit from recycle of reclaimed CFC-11. If necessary, a small distillation unit could be employed to purify reclaimed blowing agent, and remove dissolved scrubbing solvent. Another advantage of liquid scrubbing is that it is a low temperature process. Degassing of scrubbing solvent can be accomplished with hot water, rather than steam, since CFC-11 has a low boiling point (24°C or 75°F).

Because experimental or pilot data for liquid scrubbing of CFC-11 are lacking, further analysis of this control technology was not performed in this study. There is some potential that this control method could evolve to compete with carbon adsorption/recycle, provided that research can uncover appropriate sorbents.

Vapor Condensation

Another control/recovery technology for CFC-11 that has been proposed is the use of refrigeration to directly condense blowing agent from the exhaust stream. Any component of a vapor mixture can be condensed if brought to sufficiently low temperature. However, the more volatile a compound, that is, the lower its boiling point, the greater the potential vapor emissions at a given temperature. The higher the concentration of a component in the gas stream, the greater will be the percent condensed at a given temperature. Both of these factors work against condensation of CFC-11 from flexible foam plant exhaust. Concentrations of CFC-11 in exhaust from slabstock plants, even with efficient vapor capture designs, would rarely exceed 10,000 ppm. Also, the boiling point of CFC-11 is relatively low (24°C or 75°F). Preliminary calculations indicate extremely low condenser temperatures below -84°C (-120°F) are necessary to achieve 90 percent condensation from an air stream containing 2,000 ppm CFC-11 (54).

At the extremely low temperatures necessary to condense CFC-11, ice formation in the condenser may pose a problem with equipment reliability. It may be necessary to partially dehumidify a large volume of exhaust air. Alternatively, two condenser coils sized to treat the entire exhaust stream would be used, with cyclic condensation/defrost periods. Another problem would be efficient removal of the condensed CFC-11 mist from the large-volume air stream. In addition to these barriers, refrigeration of the large exhaust stream would be extremely energy intensive, and would far outweigh any savings in foam raw material obtained from reclaimed auxiliary blowing agent.

SECTION 6

SUBSTITUTE AUXILIARY BLOWING AGENTS

One type of emission control measure that offers considerable promise in reducing CFC-11 emissions in manufacture of flexible polyurethane foam is substitution of another auxiliary blowing agent. Use of alternative blowing agents could eliminate, or significantly reduce, the CFC-11 emissions associated with flexible foam production. One such substitute, methylene chloride, is currently used as an auxiliary blowing agent for many grades of flexible slabstock. Another potential option is the use of mixtures of CFC-11 with other volatile compounds which could partially replace pure CFC-11 for certain foam products. Several proprietary blends are commercially available from suppliers of auxiliary blowing agents (7,8). Also, other developmental fluorocarbon compounds not currently available commercially have properties suitable for foam blowing agents (55). Further development of the "newer" CFCs is in progress, or could be initiated, with the goal of auxiliary blowing agent substitution.

The following discussions will emphasize methylene chloride, hydrocarbon blends, and other CFC compounds as alternative blowing agents, since these technologies are the most developed or show the most promise. Omission of the auxiliary blowing agent, resulting in a soley water-blown foam, is also an available alternative. But with conventional chemical systems, there exist serious limitations in the range of foam properties attained. There are polyol/isocyanate systems that are intended to reduce the limitations of water-blown foam, and these are described in Section 8.

METHYLENE CHLORIDE

Recent industry experience indicates that substitution of methylene chloride for CFC-11 can eliminate CFC emissions in flexible foam manufacture for a significant range of slabstock foam grades. Since 1982, the use of methylene chloride nearly equals CFC-11 use in slabstock production (3,32,56). While a substantial shift to methylene chloride has occurred in recent years, many sources have stated that the degree of substitution could expand in the future (3,27,57). A key obstacle to such expansion, however, is the as-yet unresolved issue of acceptable exposure levels for methylene chloride. Due to the solvent properties of methylene chloride, substitution is not presently thought to be feasible for molded foam products. Therefore, most of the following discussion will apply only to the flexible polyurethane slabstock industry segment.

Equipment and Procedure Modifications

Current manufacturing practices indicate that slabstock processes and operating procedures do not require extensive changes when methylene chloride is employed. The ability of many producers to switch between methylene chloride and CFC-11 for different grades of foam is evidence of this.

Perhaps the key in successfully applying methylene chloride substitution is determining appropriate feed formulations. Published, or commercially available formulations are usually only the starting point, because each foam producer has a different situation. Common practice is to slightly modify a formulation that is known to work, and this requires an understanding of the different component interactions. Since methylene chloride has a higher boiling point and higher heat of vaporization, the foam exotherm must be greater to evaporate the agent. Until the early 1980's it was difficult to overcome methylene chloride's delayed volatilization and tendency to reduce foam porosity. Advances in catalyst technology since that time have made it possible to greatly extend the range of methylene chloride use, by allowing the timing of reactions involved in foam formation to be altered.

In flexible foam manufacture, two types of catalysts are used. First, an amine catalyst controls the rate of reaction between water and isocyanate, termed the blowing reaction since carbon dioxide and heat are liberated. Second, a tin catalyst (e.g. stannous octoate) is used to modify the rate of urethane monomer formation and consequent foam gelation. These compounds act in a synergistic manner. The relative activity of each is critical in producing, with methylene chloride, foams having the same quality as CFC-11 blown materials.

Development of "delayed" amine catalysts has permitted use of up to 25 parts methylene chloride per hundred polyol in slabstock formulations (27,32, 58). Prior to these advances, foam formulations were limited to about six to eight parts methylene chloride per hundred polyol; higher levels would result in splitting of the bunstock. These less active amine catalysts permit control of the rate of urethane polymerization to achieve better balance with the volatilization of methylene chloride. Examples of commercial amine catalysts include Abbott Labs Polycat-12®, Air Products Dabco WT®, and Union Carbide Niax catalyst A-200®.

Generally, the catalyst package must be tailored to accommodate the alternative blowing agent and specific equipment characteristics. Blends of commercial catalysts are widely used, since no one catalyst system will work best with methylene chloride in all cases. For instance, a weak amine may be blended with a strong blowing amine to deliver as system that fits a producer's specific needs (32). It has been found that higher levels of tin catalyst are required to maintain foam porosity (which is related to foam density) as methylene chloride content is increased. This is illustrated in Figure 6-1 (33).

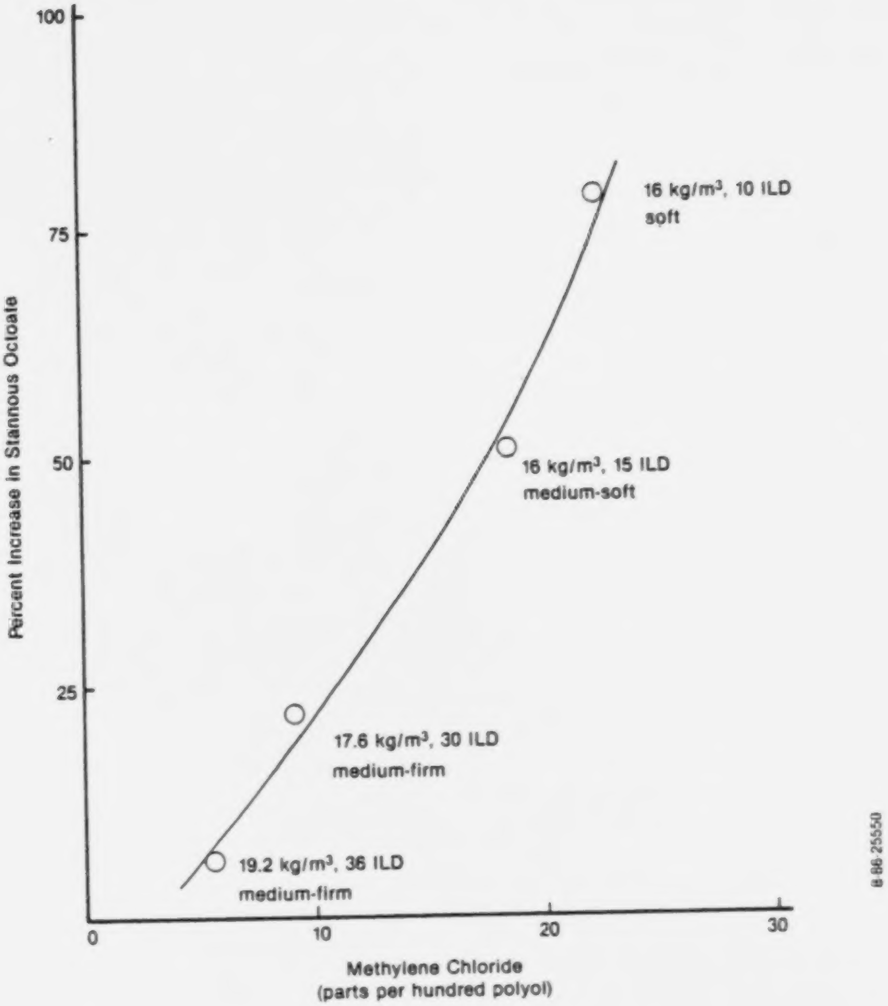

Figure 6-1. Effect of methylene chloride blowing agent on tin catalyst required to maintain foam porosity.

Source: (32)

Testing of new formulations can present a major economic obstacle to foam producers, who must absorb the development costs. At typical slabstock production rates (200 kg/min), raw material supply costs for formulation tests could exceed $400/min. A possible alternative to such costly trials is small-scale tests in a laboratory setting. Testing equipment is available that measures the rise rate of a small test batch of foam (32,59). Simple experimental procedures have also been developed to provide information on foam rise and gelation rates (37). Such tests offer a screening method to compare the rise behavior of a new methylene chloride formulation with a proven CFC-11 blown foam. Use of small-scale tests could reduce the risk in expanding the utilization of methylene chloride. But test runs on the actual process equipment are still necessary to verify the bun rise characteristics and the control sensitivity of a new formulation.

In practice, it has been found that metering of the feed formulation must be more carefully controlled when methylene chloride is used. This generally requires greater attention and skill on the part of the line operating crew. More precise timing of the foam reactions is necessary to ensure foam quality, and this requires accurate blending of catalysts and feed materials. Moreover, control of the process becomes more sensitive to changes in temperature, barometric pressure and random variations in raw material quality. In combination these factors can result in a higher scrap rate for methylene chloride blown foam; and this is a key economic concern of foam producers.

Methylene chloride emissions occur over an extended period during the foam production process, compared to CFC-11 release. Indicative of this is the characteristic foam temperature versus time profile; while CFC-11 blown foam reaches its peak temperature within the foam tunnel, methylene chloride blown foam may continue to heat beyond the tunnel. This is a consequence of the delaying catalyst activity in methylene chloride formulations. The delayed temperature rise, together with the higher boiling point, cause methylene chloride's volatilization and diffusion out of the foam to be slower.

Due to its slower emission rate from the bunstock, significantly more methylene chloride is released in the bun curing step than CFC-11. Data recently collected at a facility using methylene chloride revealed that 33 to 45 percent of the blowing agent was released during bun curing and storage (60). In contrast, industry studies of CFC-11 emissions within slabstock plants have found that only 10 to 30 percent of the original CFC charge remains in the foam beyond the bun cut-off saw (13,52). So, additional ventilation may be required in the bun curing area to maintain ambient concentrations below the TLV for methylene chloride (current standard is 500 ppm). A discussion of engineering design and costs in a following section provides cost estimates for retrofit of additional curing area ventilation in typical plants.

Present evidence suggests that methylene chloride may not be a significant threat to the environment, or a health hazard to individuals in the vicinity of a foam plant, provided the emissions are dilute. However, studies are continuing in this area and emissions of this blowing agent could be subject to future regulation by EPA, OSHA or individual state agencies. Therefore, control cost estimates for methylene chloride substitution should also account for possible retrofit of carbon adsorption, or other blowing agent emission control technology.

Plant equipment modifications to accommodate methylene chloride include separate storage and pumping hardware. Solvent-resistant fittings and gaskets made of vinyl, fluoropolymer, or fluorinated elastomer must be used throughout. Most slabstock manufacturers have already made this investment. It is noteworthy that while a CFC-11 storage tank must meet a pressure vessel rating, this is not necessary for methylene chloride storage facilities (58). Essentially all slabstock pouring equipment currently in use is compatible with methylene chloride.

Methylene Chloride for Molded Flexible Foams

To date, methylene chloride has proven unsuitable as an auxiliary blowing agent for molded flexible foam production, because of its stronger solvent properties compared to CFC-11. Since there is less opportunity for the blowing agent to escape from the mold, retention time in the foam cells during polymerization is extended. This causes a breakdown in the stability of the foam polymer cells, and the foam may "collapse." A less resilient, more sticky foam is produced, which is not suitable for automotive or furniture manufacture (34,35).

A considerable amount of methylene chloride is used in molded foam plants as a solvent for mold cleaning and application of demolding agent (4,5,38). Non-volatilized liquid is generally recovered from such operations.

There is evidence that commercially-available mixtures of methylene chloride and CFC-11 may be suitable for some molded foam products. It may be possible to replace up to 20 percent of the CFC-11 used without detrimental effects on product quality (8,18,61). Information in this area is very limited, probably because the major molded foam producers in the United States have not widely adopted these blends. As discussed in Section 8, increased application of water-blown formulations, in conjunction with the HR process, is also seen as an effective option for reducing CFC-11 emissions from molded foam production (15,37).

Control Effectiveness

An advantage of methylene chloride substitution in flexible foam production is that significant reductions in CFC emissions could be realized over the near-term. The availability of this control technology is excellent, since it is already widely applied. A majority of flexible slabstock producers have experience in the application of methylene chloride. Also, there is a substantial reservoir of expertise within the foam chemical industry to ease further conversion.

It has been postulated that it is technically feasible to substitute methylene chloride for CFC-11 over an expanded range of foam grades. These foams represent 50 to 75 percent of slabstock volume currently produced using CFC-11 (18,27,35,58). Given present development trends, it is possible that methylene chloride could be used in the future for softer and/or less dense foams. As much as 90 percent of current flexible slabstock output produced with CFC-11 could be converted to methylene chloride blowing agent if somewhat higher foam densities were adopted (27,32,37).

With present industrial practices CFC-11 is the preferred blowing agent for low foam densities of about 20 kg/m^3 (1.2 lb/ft^3) or less, since substitution of methylene chloride has proven increasingly difficult for production of lower density foams. The extent of applicability near this threshold usually depends on the expense and effort each foam producer is willing to devote to conversion. Because of technical limitations, low-density foam products cannot be made at certain facilities using presently available methylene chloride blowing technology.

Also, there remains a degree of inertia among some foam producers to reduce the use of CFC-11. About ten percent of the CFC-11 used by all slabstock producers is used by foamers who do not see methylene chloride as a viable alternative for them, and thus use only CFC-11. Typically, these are small size operations that may be marginally profitable, or technically incapable of operating with the more sensitive control required for methylene chloride formulations.

Table 6-1 summarizes the cost effectiveness of methylene chloride substitution as a means of CFC-11 emission control. Three scenarios are examined; substitution with no plant modifications, and substitution with retrofit for additional curing room ventilation both with and without carbon adsorption/solvent recovery. Another key factor in this analysis is the incremental

TABLE 6-1. CFC-11 EMISSION CONTROL COST EFFECTIVENESS FOR METHYLENE CHLORIDE SUBSTITUTION IN SLABSTOCK FOAM PLANTS

	Plant Modifications:	No Change		Curing Area Ventilation		Curing Area Ventilation and Carbon Adsorption Treatment of Plant Exhaust
Percent Increase in Scrap As Result of Conversion	Annual Foam Production Rate: (thousand mt/yr)	0.5	4.0	0.5	4.0	4.0
0	Net Annual Cost[a] (credit) $1,000/yr	(34)	(274)	(19)	(174)	182
	Net Control Cost[b] (credit) $1,000/mt CFC	(1.4)	(1.4)	(0.7)	(0.8)	0.9
5	Net Annual Cost (credit) $1,000/yr	0	0	15	100	456
	Net Control Cost (credit) $1,000/mt CFC	0	0	0.5	0.5	2.2
10	Net Annual Cost (credit) $1,000/yr	34	274	49	374	729
	Net Control Cost (credit) $1,000/mt CFC	1.4	1.4	1.9	1.8	3.5

[a] Net annual cost (credit) = Annualized Operating costs (Table 6-5) - Substitution cost credit - Recovery cost credit.

[b] Net control cost (credit) ($1,000/mt CFC) =

$$\frac{\text{Net annual cost (credit)}}{\text{Foam output (mt/yr)} \times \dfrac{\text{(0.06 mt CFC-11)}}{\text{mt Foam}} \times \text{(0.86 fraction substituted)}}$$

increase in foam scrap rate due to conversion, which was varied from 0 to 10 percent. The plant characteristics and production parameters assumed in this analysis are identical to those outlined in Section 5. Two model plants with output levels of 0.5 and 4.0 thousand metric tons per year were assumed to have 950 m^2 (10,000 ft^2) and 3,800 m^2 (40,000 ft^2), respectively, of bun curing space for which retrofit floor-level ventilation systems were provided. A carbon adsorption/recycle unit treating both curing room and slabstock tunnel ventilation streams was included for recovery of methylene chloride blowing agent, although other solvent recovery methods could also be applied. The discussion later in this section more completely describes the engineering design and economics of these plant modifications.

To estimate nominal raw material savings, the total rate of material consumption for a 220 kg/min (450 lb/min) slabstock plant was approximated to average $350/min at mid-1985 prices. Based on previous studies, which stated that methylene chloride conversion could provide material cost savings of 2 to 7 percent (18,27), an average savings of 5 percent was presumed. Also, all slabstock having an ILD index greater than 15, or 86 percent of foam produced (see Table 6-6), was assumed to be produced with methylene chloride. This corresponds to an average methylene chloride content in the foam feed of 5.1 weight percent which was taken to equal 85 percent, by weight, of the CFC-11 replaced.

As shown in Table 6-1, the incremental increase in foam scrap rate is a critical factor in the actual cost of methylene chloride conversion. Depending on the increase in this rate, it is possible for a foam producer to realize a net savings or expense, whether or not additional plant ventilation is installed. In no case was a net cost savings calculated if carbon adsorption was required. On the basis of cost per metric ton averted CFC-11 emission, the net control expense is also highly sensitive to foam scrap rate. Under the most likely conditions, i.e., an increase in scrap of about 5%, control costs could range from essentially negligible to about $3,500/mt if carbon adsorption is included in the control package.

Enforceability is also an issue when considering substitution of methylene chloride. Most slabstock producers already have the capability to use either CFC-11 or methylene chloride blowing agent; so control of CFC-11 might best be effected at the point of raw material purchase. This could restrict the production profile for certain manufacturers, because quantities of the different foam grades produced can fluctuate widely. If certain products are exempted from methylene chloride substitution, then it will be difficult to insure that a given product is made with the specified agent.

Safety and Environmental Factors

In switching from CFC-11 to methylene chloride, a foam producer must recognize that the toxicity and exposure risks associated with this alternate blowing agent are still under evaluation. A number of studies have investigated the potential health hazards of work place exposures to methylene chloride. Methylene chloride is currently rated as an indefinite animal carcinogen (40) and it has been recommended that it be labeled a probable human carcinogen (62). However, recent reexamination of health effects data has suggested a downward revision of the calculated risk from methylene chloride stack emissions from foam manufacturing plants.

The Threshold Limit Values (TLV) for CFC-11 and methylene chloride provide an indication of their relative toxicity. CFC-11 has been assigned a TLV of 1000 ppm, the highest allowable (least toxic) rating for gases (63). The current OSHA 8-hour permissible exposure level (PEL) for methylene chloride is set at 500 ppm. ACGIH has set the 15-minute TLV, and NIOSH has set the 1-hour ceiling TLV, at 500 ppm as well. These latter two agencies have promulgated time weighted average TLV at 100 and 75 ppm for methylene chloride (40).

Methylene chloride generally enters body by absorption in the lungs, less often via absorption through the skin. It has been hypothesized that the body can metabolize methylene chloride to carbon monoxide (as carboxyhemoglobin) which accounts for the mild depression of the central nervous system upon acute inhalation or ingestion. Studies performed to date on methylene chloride toxicity with respect to carcinogenesis have delivered conflicting conclusions (62).

Workers in flexible foam facilities represent a prime risk group for methylene chloride-related health effects. Perceptions of a hazard on the part of workers is sometimes cited as having a detrimental effect on productivity and quality control. The odor of methylene chloride, compared to odorless CFC-11, contributes to this negative perception. There are little publically available data on the in-plant concentrations of methylene chloride occurring in slabstock plants.

Protective devices are available which would reduce inhalation exposure to methylene chloride. Several varieties of half- or full-face respirator masks with activated carbon cartridges, or air-supply respirators, would ensure inhaled concentrations below current and proposed TLV's for methylene chloride (i.e., less than 50 ppm). However, it cannot be assumed that such precautions will meet the approval of OSHA and other agencies. With respect to overall costs of methylene chloride conversion, additional expenditures for protective gear would be small compared to expenditures for improved plant ventilation systems. Evaluation of appropriate ventilation levels would still be recommended for each slabstock production facility.

Like CFC-11, methylene chloride is essentially nonflammable under the conditions encountered in normal foaming operations. However, precautions should be taken to avoid release or combustion in the event of a plant fire or explosion, since incineration of the compound can release hydrochloric acid, and chlorine gas.

To date, no long-term environmental effects have been identified as resulting from methylene chloride release. Absorption into surface waters does occur to a small extent, but the short evaporative half-life (i.e., high volatility) of methylene chloride in water does not allow accumulation and the absorbed compound is returned to the atmosphere (62).

Methylene chloride is not recognized as an ozone-depleting substance due to its relatively short residence time in the atmosphere, and is also currently exempt as a regulated Volatile Organic Carbon (VOC) emission. Chlorofluorocarbons appear to have atmospheric lifetimes of 20 to 110 years, while methylene chloride is estimated to remain in the atmosphere no more than 6 months. It is currently thought that this is a result of methylene chloride reactions with hydroxyl radicals in the lower atmosphere (27).

Current Status

A majority of flexible slabstock foam producers have acquired the capability to use either CFC-11 or methylene chloride as an auxiliary blowing agent. Out of 97 facilities identified as producers of flexible slabstock foam in 1985, 58 used methylene chloride as an auxiliary blowing agent to some extent. It has been estimated that about 12 thousand metric tons (22.6 million lbs) of methylene chloride was used by these foam producers in 1985 (5).

Over the past decade, there has been an increase in the portion of foam output produced using methylene chloride. Also during this period, the weight of CFC-11 used as a percentage of the foam feed material declined from 2.9 to about 2.5 percent of the total weight of flexible slabstock produced. Both of these trends in the usage distribution for the two blowing agents are depicted in Table 6-2.

Since 1982, the quantity of slabstock foam blown with methylene chloride has remained about equal with that blown with CFC-11 (32,37,45). This is primarily a result of the economic advantage of the less expensive blowing agent, and industry concern about regulations restricting CFC-11 use. More recently it appears that application of methylene chloride blowing agent has actually declined. Interviews with several suppliers of foam manufacturing equipment and chemicals have indicated that fewer slabstock producers are

TABLE 6-2. HISTORIC DISTRIBUTION OF THE MAJOR AUXILIARY BLOWING AGENTS FOR FLEXIBLE POLYURETHANE SLABSTOCK FOAMS

	Percent of Slabstock Foam		Weight CFC-11 Used as a
Year	CFC-11	Methylene Chloride	percent of all Slabstock
1977	70	30	2.9
1979	65	35	2.8
1982	50	50	2.6
1984	50	50	2.5
1985	53	47	NA

NA = Not Available

Sources: (1,2,3,4,5)

using methylene chloride than in the past (10,37,38). One frequently cited reason for this reversal is continuing difficulty with product quality when methylene chloride is used. However, such judgements are often made on a subjective basis. In some instances, the reason for conversion away from methylene chloride has been the implementation of stringent emission standards at the state level.

Based on historic and current prices for both CFC-11 and methylene chloride there is a significant advantage in raw material cost for the latter blowing agent. The cost of the auxiliary blowing agent usually accounts for 5 to 15 percent of total raw material costs. Based on 1985 market prices for the two blowing agents (36,64), conversion to methylene chloride can provide material savings of $100 to $250 per metric ton of foam, depending on density and firmness grade.

Substitution of CFC-11 with methylene chloride has not occurred to any significant extent in Europe. This is primarily attributed to possible toxicity concerns and lower methylene chloride TLV standards than in the United States. For example, in the United Kingdom, the current TLV is 100 ppm and some countries may lower this to 50 ppm (50). Capital expenditures for ventilation to maintain ambient conditions at or below this level are generally prohibitive. There has been one new installation in the United Kingdom expressly designed for methylene chloride use, but this required an extensive underfloor ventilation system (50). In Europe, there has been more aggressive innovation in the area of new foam processes which can dramatically reduce or eliminate the need for auxiliary blowing agents. Some of these technologies will be discussed in Section 8 of this report.

Concerns about methylene chloride toxicity have not eliminated its application as a general solvent in flexible foam manufacture. In both slabstock and molded facilities, it is widely used for flushing of dispensing heads, mold cleaning, release compound carrier, and spillage cleanup. This use accounts for most of the methylene chloride consumption by molded foam producers, which in 1985 was estimated to be 3.1 thousand metric tons (5).

Engineering Design Analysis

To more carefully quantify the technical and economic factors involved in substitution of methylene chloride, engineering and cost analyses have been performed for retrofit installation of additional ventilation in bun curing and storage areas. Estimates were prepared for two sizes of slabstock plant, in order to examine the influence of plant size. Since it is possible that add-on controls will have to be applied to contain methylene chloride emissions from slabstock foam plants, the additional costs for a carbon adsorption system are included for one example plant size. Quantitative trade-off evaluations between these costs and material savings with methylene chloride are subject to large uncertainties since equipment retrofit costs are highly site-specific.

The example slabstock plant used here for estimating the cost of CFC-11 emission control by methylene chloride substitution is, in most respects, identical to the example slabstock plant used to evaluate carbon adsorption/recycle of CFC-11 (see Section 5). However, a different assumption in this analysis is that the entire slabstock output is produced using methylene chloride blowing agent.

Capital Costs--

Capital investment for retrofitted curing room ventilation systems were estimated for two facilities having different sized curing areas. Curing rooms of 980 m^2 (10,000 ft^2) and 3,800 m^2 (40,000 ft^2) were selected as representative for a range of existing slabstock plants. Based on mass balances around the example plant described in Table 5-3, it was possible to calculate a typical amount of fresh bunstock introduced daily to the curing room per unit floor area (i.e., 17 kg/m^2 curing area). This factor was assumed to apply to both sizes of curing room considered here.

Data compiled from a typical slabstock plant were used to calculate the amount of methylene chloride released in the curing room per unit fresh foam (60). These data indicated that, on average, 30 kg methylene chloride were released in the curing area per metric ton foam. This represented about 35 to 40 percent of the initial charge of the auxiliary blowing agent depending on the foam grade. Based on this release rate, and assuming a 6 meter (20 foot) ceiling in the curing room, an adequate ventilation rate was calculated to maintain ambient room methylene chloride concentration at 100 ppm or below. The estimated flow rates were 9.5 Nm^3/s (22,000 cfm) and 37 Nm^3/s (86,000 cfm), respectively, for the large and small curing areas.

A conventional duct work design employing floor-level exhaust grilles was developed to provide a basis for equipment costing. Purchased equipment costs for the curing area ventilation systems were obtained from Means Construction Cost Index for 1985, for a conventional galvanized steel, rectangular duct installation, including rotary ceiling ventilators and centrifugal exhaust fans (65). Floor level exhaust ports may not be the optimal vapor capture strategy for all slabstock plants; this would have to be evaluated for each installation. Itemized equipment cost estimates are shown in Table 6-3.

The cost estimate for carbon adsorption/recovery of methylene chloride for the larger capacity example plant was based on design criteria outlined in Section 5. An adsorber system similar to that depicted in Figure 5-8 was considered, but expanded to include 4 beds in parallel. More adsorbent beds would be needed to accommodate the combined exhaust flows from the foam tunnel and curing areas. It is anticipated that three beds would be on-line simultaneously; two treating curing area exhaust, one the foam tunnel exhaust, with the fourth being regenerated by hot air circulation. To maximize utilization of carbon capacity, a freshly regenerated bed would initially filter the more dilute curing room exhaust, and would then be switched to foam tunnel exhaust.

This operating cycle minimizes the number of beds required to treat 50 Nm^3/s (116,000 cfm). Inclusion of an air/steam heat exchanger is necessary, since significant water solubility of methylene chloride would probably preclude steam regeneration. Desorbed methylene chloride could then be condensed from the air stream by a water-cooled condenser. The exhaust rate

TABLE 6-3. CAPITAL COST ESTIMATE FOR FLEXIBLE FOAM PLANT MODIFICATIONS ASSOCIATED WITH METHYLENE CHLORIDE SUBSTITUTION

	Retrofit Ventilation in Bun Curing Area only		Retrofit Ventilation for 3,800 m^2 Curing Area, With 4-Bed Carbon Adsorption for MeCl Control
Modification:	950 m^2 (10,000 ft^2)	3,800 m^2 (40,000 ft^2)	
Air Handling Requirement:	9.5 Nm^3/s (22,000 cfm)	37 Nm^3/s (86,000 cfm)	50 Nm^3/s (116,000 cfm)
Direct Capital		(Cost in $1,000, mid-1985)	
Carbon Beds (316SS) with instruments, controls, valves, regeneration fans, condenser and heat exchanger,	–	–	510[a]
Boiler, 6800 kg/hr (15,000 lb/hr)	–	–	56[a]
Revamped Tunnel Enclosure	–	–	15
Ductwork:			
curing area[b]	5	20	20
foam tunnel and adsorber	–	–	15
Ceiling Ventilators[b]	2	7.5	7.5
Exhaust Fans[b]	7	28	33
Recycle MeCl Pump, dryer, storage	–	–	9
Cooling Tower, Pump/Water	–	–	80[a]
TOTAL PURCHASED EQUIPMENT COST	14	55.5	745.5
TOTAL INSTALLED DIRECT COST[c]	28	111	1250

(Continued)

TABLE 6-3 (Continued)

Modification:	Retrofit Ventinlation in Bun Curing Area only		Retrofit Ventilation for 3,800 m^2 Curing Area, With 4-Bed Carbon Adsorption for MeCl Control
	950 m^2 (10,000 ft^2)	3,800 m^2 (40,000 ft^2)	
Indirect Capital (% of direct capital)			
Engineering and Supervision at 10%	2.8	11.1	125
Misc. Field Construction Expenses at 5%	1.4	5.5	62.5
Contractor Fees at 10%	2.8	11.1	125
Contingencies at 20%	5.6	22.2	250
Startup Expenses at 2%	.3	1.1	2.5
Interest During Construction at 10%[d]	2.8	11.1	125
TOTAL INDIRECT CAPITAL	15.7	62.1	690
TOTAL DEPRECIABLE CAPITAL (TDC + TIC)	43.7	173.1	1940
Working Capital[e]	1.6	12.9	34.5
TOTAL CAPITAL INVESTMENT	45.3	186	1974.5
(round-off)	50	190	1980

[a] Calculated by extrapolation of costs for 3-bed CFC-11 carbon adsorber (Table 5-4) to 4-bed system at 50 Nm^3/s flow rate and 6800 kg/hr steam demand.

[b] Equipment costs from Means Construction Cost Index, 1985 (65).

[c] Estimated to be 100 percent of curing area ventilation equipment and 65 percent of remaining equipment.

[d] 10% per year with one year construction period.

[e] At 25% of direct operating and maintenance costs.

from the tunnel was taken as 13 Nm^3/s (30,000 scfm), and the enclosure was presumed to be modified to reduce ventilation air volume and maximize blowing agent vapor capture as suggested in Section 5. These modifications were assumed to include enclosure of the foam conveyor beyond the tunnel itself, restriction of tunnel entrance and exit openings, and positioning of exhaust grilles below the conveyor. The same costs for tunnel enclosure, connecting duct work, and auxiliary pumping equipment are used as in the CFC-11 adsorption system described in Section 5.

To derive equipment cost estimates, capital costs for the CFC-11 recovery system described in Section 5 were scaled-up to account for working capacity in methylene chloride adsorption service and for a 4-bed system treating approximately 17 Nm^3/s (39,000 cfm) per bed. Costs for a 4-bed adsorber, 6,800 kg/hr (15,000 lb/hr) steam boiler, and condenser water cooling tower were estimated as shown in Table 6-3, based on mid-1985 dollars. A purification system for the reclaimed methylene chloride was not included, since the material would likely need to be hauled off site for purification and reformulation with additives.

Direct installation costs were estimated to be equal to 65 percent of the equipment costs for the carbon adsorption system, and equal to 100 percent of the equipment costs for the more labor-intensive fabrication of the curing area duct system (65). Indirect capital costs were calculated based on generally accepted estimating factors relative to the direct costs (51). In total, these factors amount to indirect capital costs equal to 57 percent of the installed direct costs.

For the curing area ventilation alone, the capital costs amounted to 50 and 135 thousand dollars, respectively, for the two example plant sizes. It is probable that this level of investment could reasonably be recovered by nearly all slabstock foam producing firms. Such might not be the case for a carbon adsorption system, which was estimated to require a capital investment of nearly $2 million. Each of these overall capital expenditure estimates are presumed to be accurate within 30 percent.

Annualized Operating Costs--

The assumed annual production level for the two example plants established a nominal number of operating days and daily operating period. On this basis, variable operating costs associated with the curing room ventilation system, and the carbon adsorption/recovery system could be estimated. Utility costs were calculated assuming that the curing room ventilation system would operate an average of four days per week. Replacement carbon costs were not considered, since the service life of the initial charge would probably extend beyond the amortized payout period of a carbon adsorption system. Heating and/or cooling costs due to additional plant intake air were also neglected. These costs would depend on plant locale, construction, and operating practices, and may in certain cases constitute a substantial incremental operating cost.

For the scenarios involving ventilation of the curing room only, the major contributions to annualized operating costs are electricity for exhaust fans and capital recovery. As in the case of CFC-11 recovery, over half of the annualized costs for the carbon adsorption system are attributable to capital recovery; steam utility expenses are about one-fifth the electricity costs for this case. When ventilation of the curing room is applied, annualized operating costs are roughly proportional to plant output; addition of a carbon adsorption system increases these costs by about a factor of five.

Based on the annualized operating costs summarized in Table 6-4, control cost effectiveness, in terms of dollars per metric ton of CFC-11 emission averted, was calculated for each retrofit scenario. An overall methylene chloride recovery rate of 50 percent was assumed to be reasonable; this corresponds to about 60 percent recovery from tunnel exhaust and 30 percent recovery of curing room releases. The results of this analysis were presented earlier in this section (see Table 6-1).

In terms of cost effectiveness, if the foam scrap rate were unchanged the example slabstock facility with retrofit curing area ventilation could realize an annualized savings of about $700-$800 per metric ton CFC replaced. Or,

TABLE 6-4. ANNUALIZED OPERATING COST ESTIMATE FOR FLEXIBLE FOAM PLANT MODIFICATIONS ASSOCIATED WITH METHYLENE CHLORIDE SUBSTITUTION

		Retrofit Ventilation in Bun Curing Area only		Retrofit Ventilation for 3,800 m^2 Curing Area, With 4-Bed Carbon Adsorption for MeCl Control
Modification:		950 m^2 (10,000 ft^2)	3,800 m^2 (40,000 ft^2)	
Assumed Annual Production; thousand mt (million lbs)		0.5 (1.1)	4.0 (8.8)	4.0 (8.8)
Operating Days/Year		50	145	145
Average Hours/Day		1	5	5
Curing Area Ventilation Day/Year		100	200	200
		(Cost in $1000, Mid-1985)		
Direct Operating and Maintenance Costs	Rates			
Operating Labor[a]	$13.00/hr	0.2	0.6	1.6
Maintenance[b]		0.8	3.3	23.9
Electricity[c]	$0.043/kwh	4.2	71	79
Steam[d]	$18.5/1000 kg/hr ($8.40/1000 lb/hr)	-	-	18.2
Process and Cooling Water[e]	$0.066/$m^3$ ($0.25/1000 gal)	-	-	5.2
TOTAL DIRECT COSTS		5.2	74.9	127.9

(Continued)

TABLE 6-4 (Continued)

	Retrofit Ventilation in Bun Curing Area only		Retrofit Ventilation for 3,800 m^2 Curing Area, With 4-Bed Carbon Adsorption for MeCl Control
Modification:	950 m^2 (10,000 ft^2)	3,800 m^2 (40,000 ft^2)	
Indirect Costs			
Capital Recovery Factor[f]	8.1	30.9	322.2
Overheads[g]	0.1	0.2	1.7
Administration[h]	0.3	1.1	6.7
Insurance & Property Taxes[i]	1.0	3.8	39.6
TOTAL INDIRECT COSTS	9.5	35.0	370.0
TOTAL OPERATING & MAINTENANCE EXPENSES	14.7	109.9	497.9
(Round-Off)	15	110	500

[a] Includes operating labor and supervision; 0.25 hr/day operating labor for ventilation, 0.5 hr/day operating carbon adsorption, supervision at 15% of labor.

[b] Includes maintenance labor, materials, and supervision and is estimated at 3 percent of the direct capital costs for ventilation, and 1 percent for carbon adsorption.

[c] 15.5 kw/Nm^3/s (5 hp/1000 cfm), curing area at 12 hrs/ventilation day, carbon system at 120% of annual operating hours.

[d] 4 kg steam/kg MeCl, 1 hr regeneration cycle/day of adsorber operation.

[e] 3.0 m^3/min (800 gpm), for 120% of annual carbon adsorber operating hours.

[f] Estimated at 16.275 percent of the total capital investment.

[g] Estimated at 38 percent of labor expenses.

[h] Estimated at 50 percent of the operating labor and 25 percent of the maintenance.

[i] Estimated at 2 percent of the total capital investment.

with no change to plant ventilation, the example plant could realize a savings of $1400 per metric ton of CFC-11 replaced, provided incremental increases in scrap rate were negligible. However, if the scrap rate increased five or ten percent as a result of conversion to methylene chloride, the example slabstock facility with curing area ventilation could instead incur an annualized cost of $500 to $1900 per metric ton CFC replaced. For the larger example plant, inclusion of carbon adsorption results in a net cost of $900-$3,500 per metric ton CFC-11 replaced, depending on scrap rate increase.

Economic Factors

There are many economic factors that can influence the selection of an auxiliary blowing agent by a slabstock producer. In practice, a majority of foamers have developed the capability to use either CFC-11 or methylene chloride depending on the relative costs. Smaller producers tend to use CFC-11 preferentially, due to greater reliability in quality control for lower volume production runs. Given the current industry status, there is a range of foam grades for which overall cost considerations favor CFC-11.

Several important economic considerations regarding the control of CFC-11 emissions by methylene chloride substitution can be identified. These include:

- Net raw material cost savings;
- Higher waste and scrap rates;
- Costs for additional plant ventilation, and/or carbon adsorption to control methylene chloride emissions;
- Cost projections for methylene chloride; and
- The impact on foam end-use markets.

Estimates of raw material cost savings associated with methylene chloride vary. Examples presented in industry journals have placed cost savings in the 6 to 7 percent range (27,32,57,66). As of 1980, the EPA reported that methylene chloride applications could save 4 to 7 percent (61). Rand Corporation has estimated the savings more conservatively at 2 to 4 percent (35). It should be noted that such estimates reflect only average cost differences; actual relative costs depend on the foam grade. In the analysis of control cost effectiveness presented previously, average savings amounting to five percent of raw material costs were assumed.

The actual raw material cost differential between CFC-11 and methylene chloride blown foams varies greatly for different foam grades, since the amount of auxiliary blowing agent used depends on foam softness. To illustrate this, Table 6-5 displays the blowing agent cost differential for average density foam, 20 to 24 kg/m^3 (1.2 to 1.5 lb/ft^3), over a range of softness grades as indicated by the ILD index.[1] Softer foams (i.e. those with lower ILD indices) offer far more savings per unit weight. However, when these savings are weighted by a typical production profile, the realized savings per unit of total foam production are greatest for the moderate softness foams.

One economic disincentive for conversion to methylene chloride is the potential for wasted raw material and high scrap rates that might have to be absorbed during line testing of new formulations, or during routine operation. For many slabstock foam lines output rates may exceed 230 kg/min (500 lb/min), with raw materials costs of several hundred dollars per minute of operation. Even a few minutes of unsalable product could offset potential savings for a small foam producer. To avoid severe problems, foam producers usually enlist the help of a chemical supplier to provide technical assistance in developing modified formulations. Another consideration is the ability of the production staff to reliably maintain quality control with the new formulation.

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[1] The ILD (Indentation Load Deflection) index refers to a standard foam specification which measures resistance to compression. Soft foams have ILD less than 12, while the firmest commercial grades have ILD greater than 40.

TABLE 6-5. INCREMENTAL BLOWING AGENT COST SAVINGS BY CONVERSION TO METHYLENE CHLORIDE FOR VARIOUS SLABSTOCK FIRMNESS GRADES

ILD[a]	Wt. Percent MeCl in Typical Formulation	$ Cost Differential Per Metric Ton of Each Foam Grade	Typical Production Profile - Percent of Output in Each Foam Grade	$ Cost Differential per Metric Ton Total Foam Output
<10	14	250	4	10
10-15	11.8	220	10	22
15-20	9.1	200	12	24
20-25	6.9	160	15	24
25-30	4.5	140	30	42
30-35	2.3	110	20	22
35-40	0	0	5	0
>40	0	0	4	0

[a] Sources: (27,32,35)

[1] The ILD (Indentation Load Deflection) index refers to a standard foam specification which measures resistance to compression. Soft foams have ILD less than 12, while the firmest commercial grades have ILD greater than 40.

What constitutes scrap depends on subjective judgement, and on the perception of the producer and the customer. It is claimed that sophisticated buyers can detect a difference in quality between CFC-11 blown and methylene chloride blown foams. This was probably true when methylene chloride was first applied and some differences in foam appearance were obvious; typically discoloration, non-uniform density, or possible odor from residual methylene chloride. More recently, foams have been produced with urethane grade methylene chloride that does not cause discoloration. Newer catalyst systems have yielded improved blowing characteristics such that the consistency of methylene chloride blown foam is indistinguishable from CFC-11 blown material. It is anticipated, however, that some incremental increase in scrap rate will occur with methylene chloride use, as a consequence of more critical process control requirements.

One tangible cost of methylene chloride substitution is the possible need for additional ventilation capacity in slabstock bun curing or storage areas of the plant. Retrofit costs for additional plant ventilation in connection with methylene chloride conversion have been addressed in this study. The annualized operating costs for increased ventilation capacity are predicted to be less than the net cost benefit resulting from the use of methylene chloride blowing agent, unless increases in scrap rates are significantly higher than five percent of total production (see Table 6-1). A factor not considered in this analysis is the need for additional space heating or cooling costs as a result of higher ventilation rates.

If carbon adsorption must also be incorporated as an add-on control for methylene chloride, then the economic outlook for this substitute blowing agent is very adversely affected. Inclusion of a carbon adsorption system increases capital investment by more than a factor of ten, compared to curing area ventilation alone; and annualized operating costs are increased by a factor of five. As pointed out with respect to adsorption/recovery of CFC-11, large capital investments could be reasonably undertaken by relatively few foam producers. An additional drawback of adsorption/recycle of methylene chloride is that the recovered blowing agent is of lower value than CFC-11, so the net recovery credit is less. However, control technologies other than carbon adsorption are applicable to methylene chloride emissions, and the economics of such systems should be evaluated.

At facilities where ventilation investment is not necessary, the cost per metric ton of averted CFC-11 emission will be relatively low, and for sufficiently low incremental scrap rates an overall cost saving may be realized. The actual costs are difficult to predict, since many plant-specific parameters are involved. The ease with which a given plant can adopt new formulations, minimize scrap, and reliably produce satisfactory quality foam will in large part determine conversion costs. Usually such costs per unit of foam produced are greater for smaller plants, which may possess less technical expertise.

At present, there exists a sufficient methylene chloride production capacity to absorb increased demand for auxiliary blowing agent (36). As of 1985, United States capacity was estimated at 320 thousand metric tons per year (710 million lbs/year) (14). Raw materials are abundant, and existing plants were operated at about 78 percent of capacity in 1985 (17). The flexible foam market consumed only about 5 percent of this output (5) and it has been estimated that complete conversion from CFC-11 would increase this portion to approximately 7 percent (17). Since methylene chloride would not be technically feasible for all existing foam grades, total new demand would be significantly less than current CFC-11 blowing agent consumption.

Barriers to Implementation and Time Frame

From an overall perspective of the United States foam market, there appear to be no extreme technical or economic barriers to near-term expansion of methylene chloride substitution as a means of reducing CFC-11 emissions in flexible slabstock production. However, further substitution of methylene chloride will probably not occur given current conditions, because of the investment required to produce sufficiently high quality foam, expenditures for ventilation upgrades and uncertainty regarding acceptable work place exposure.

Until recently, it was common practice for foamers to first investigate methylene chloride as a blowing agent for most foam grades, to take advantage of cost benefits. CFC-11 was used in the event that reformulation trials were unsuccessful, or if cost savings were not realized. For existing formulations, the switch over involved modifying the feed blend as needed to accommodate methylene chloride, rather than developing a completely new formulation. These efforts were assisted by emphasis in catalyst research and development on improving methylene chloride systems. Two reasons can be given to explain why this past tendency toward increased blowing agent conversion has reversed itself.

First, it has proven increasingly difficult to successfully reformulate for softer and less dense foams. Improved catalyst systems and new polyols with viscosity characteristics tailored to methylene chloride are available, but these foam grades represent a smaller portion of the total market. This means that development costs cannot be justified for the smaller volume products, even though on a dollar per pound basis the blowing agent savings promise to be larger.

Second, natural market forces have brought the use of methylene chloride to a mature, stable position. The economic incentive to encumber the expense of additional switch over from CFC-11 has declined. This is reflected in the observation that the relative shares of the blowing agent market for both methylene chloride and CFC-11 have remained about equal for about the past three years, while in the five years previous to that the portion of flexible polyurethane slabstock produced using methylene chloride use grew by 67 percent (1,2,18).

Capital expenditures represent an obstacle for those foamers that do not already use methylene chloride. Even if additional ventilation is not necessary, new chemical storage and delivery hardware must be installed. Solvent resistant gasket and fitting materials must be used throughout the methylene chloride system, adding to its cost. However, a majority of foamers have made this investment, so the economics of this retrofit are not highly prohibitive. This is not true if carbon adsorption were required to control methylene chloride emissions; the level of capital expenditure for typical plants would then increase by about a factor of ten.

Some barriers to methylene chloride application are related to subjective criteria, or bias on the part of foam producers. Decline in product quality is perceived by many foam manufacturers as a significant disincentive to maximum utilization of methylene chloride. Companies that use only CFC-11, generally see no feasible alternative that will provide the desired foam quality. It is sometimes claimed that even a temporary or small change in product quality will result in a loss in competitiveness. Facilities which currently use only CFC-11 may not have adequate technical expertise to adopt the more sensitive methylene chloride formulations. Or, these foamers may have discontinued their use of methylene chloride due to operating problems. A 1982 study estimated that about 10 percent of all slabstock producers used only CFC-11 (5) while a 1985 survey of 62 slabstock facilities indicated that 47 percent used CFC-11 exclusively (3).

An important barrier to implementation of methylene chloride substitution is the as yet unresolved question regarding toxicity effects associated with work place exposure. One potential problem cited by foam producers is that the lower odor threshold of methylene chloride can increase the perception of danger among the line crew, and cause increased complaints. However, on balance it should be noted that methylene chloride is not significantly more or less harmful than other commonly used industrial solvents. The flexible foam industry has evolved with CFC-11 as the dominant blowing agent, and ventilation rates have been designed to minimize risk of operator exposure to a recognized toxic foam constituent: toluene diisocyanate. As a result workers have in the past only been required to wear minimal protective gear, such as gloves and goggles. It is anticipated that use of respirator masks, in conjunction with adequate ventilation, would provide satisfactory protection. However, OSHA and other agencies would have to approve the routine use of this equipment under normal, non-emergency conditions. In summary, it must be emphasized that more research into methylene chloride release characteristics is needed to ensure the safety of its expanded use as an auxiliary blowing agent.

Any proposed time frame for methylene chloride substitution as a method of CFC-11 control would be highly variable. First, there are a number of unknowns with regard to methylene chloride toxicity and definition of safe workplace exposure levels. Second, since methylene chloride technology is essentially in-place in most of the slabstock industry, the remaining segment may represent those producers for which conversion is most difficult and/or costly.

Reasonable timing for implementation of this control should allow at least one to two years investigation on workplace concentration levels and specific economic displacements. Some of this work is currently underway. Based on the findings of this work, actual implementation could be expected to take an additional year, assuming regulations on methylene chloride emissions are not promulgated at the Federal, state, or local levels. It may be advisable to examine a phased implementation approach in order to maximize industry cooperation and reduce detrimental economic impacts. If hydrocarbon emission controls are part of methylene chloride substitution, then an appropriate timetable would be at least five to ten years. This additional time would be necessary to resolve some remaining technical issues related to blowing agent emission control through pilot testing and commercial-scale demonstrations. Another possibility is that required emission controls for methylene chloride would discourage its use, and other CFC-11 control measures would be preferred.

ALTERNATIVE CFC BLOWING AGENTS

The two characteristics of chlorofluorocarbons that can theoretically lead to depletion of atmospheric ozone are their high stability and the inclusion of chlorine in the CFC molecule. Therefore, the ozone depletion potential of this particular class of chemicals can be reduced by making the CFC molecule marginally less stable, so that it would not survive long enough to reach the upper atmosphere. Conversely, it should not be so unstable as to degrade in the lower atmosphere and contribute to smog. Hydrogen-containing CFC compounds have been identified as generally having satisfactory intermediate stability.

Alternatively, if chlorine atoms were not present in the CFC molecule the resulting species could not release the chlorine radicals that are hypothesized to react with stratospheric ozone. Fluorocarbon compounds, which do not contain chlorine, may be suitable substitutes for blowing agents such as CFC-11, since fluorine is apparently not involved in the ozone depletion mechanism.

Acceptable alternative CFC foam blowing agents must also meet several crucial processing criteria, such as suitable boiling point temperature and vapor pressure, and negligible solvency or reactivity with the polyurethane polymer. It is also desirable that the substitute material have low toxicity and low or non-flammability.

From 1975 through the early 1980s, DuPont, the major manufacturer of CFCs, expended significant effort to explore potential alternative chemicals having low ozone depletion potential (55,67,68). These studies tentatively identified three CFC compounds which could be technically feasible as flexible foam blowing agents:

- CFC-123 $(C_2HCl_2F_3)$

- CFC-133a ($C_2H_2ClF_3$)
- CFC-141b ($C_2H_3Cl_2F$)

To date, the DuPont studies and a recent evaluation by Radian (69) are the main sources of information regarding testing and commercialization potential of these materials. One major barrier in evaluating these newer, non-commercial chemicals is that many developmental details are held as proprietary by DuPont. Another is that these chemicals are generally available only in very small quantities, or as laboratory-made samples, so industrial trials have only been performed on a limited basis.

Of the three proposed chemicals, CFC-123 (2,2-dichloro-1,1,1-trifluoroethane), appears to have the most suitable properties for use as a foam blowing agent (68,70). Its boiling point of 28°C (82°F), is within the acceptable range, and its vapor pressure and heat of vaporization are similar to CFC-11 (69). It is non-flammable and based on test results to date, appears to have low toxicity (67,68). However, consideration of this compound as a substitute for CFC-11 has not proceeded because lack of an assured market has hindered development of a commercial production process.

Full-scale industrial trials of flexible slabstock production have been successfully conducted using CFC-123 as a substitute blowing agent (68). These tests demonstrated that CFC-123 could be directly substituted for CFC-11 in the foam formulation without modification of normal processing operations and procedures. Sufficient quantities of CFC-123 for these tests was obtained from a by-product stream of another CFC process; however, it is not thought that this route is practical for commercial production of CFC-123. Details concerning the physical and economic limitations on CFC-123 production have not been made available. However, it has recently been reported that lack of a suitable catalyst is a major obstacle in commercialization of substitute CFCs (71).

Two potential negative factors with respect to CFC-123 are its noticeable solvent action in polyurethane, and its higher molecular weight. In trial production of flexible slabstock foam it has been observed that the solubility of polyurethane in CFC-123 is detectable, but not as high as in methylene chloride (68). If the solvent strength differs from CFC-11, it will be necessary to test the capability of CFC-123 to reliably produce molded foam parts, since solvent affinity can adversely affect the uniformity and surface quality of molded foams. Because CFC-123 has a higher molecular weight than CFC-11, about 20 percent more blowing agent by weight is needed per unit of foam, to obtain equivalent blowing agent vapor volume (68).

Another CFC compound that has been considered as a substitute flexible foam blowing agent is CFC-133a (1-chloro-2,2,2-trifluoroethane). Application of this auxiliary blowing agent also appears to be technically feasible, but toxicity testing reported by DuPont has identified CFC-133a as embryotoxic (55,67).

Pure CFC-133a has a normal boiling point considerably lower, and a pure component vapor pressure somewhat higher, than conventional flexible foam blowing agents. But, because this particular CFC molecule is strongly solvated by the foam liquid components, its boiling temperature within the foam matrix is effectively elevated (68). This strong solvent tendency of CFC-133a could cause problems with the consistency and surface texture of the foam product, especially for molded foam parts. It is also possible that the boiling point and vapor pressure characteristics of the solvated blowing agent will depend on the nature of the feed components. This implies that careful testing of each foam formulation would be necessary to ensure product quality.

A third CFC compound which has been identified as a potential flexible foam blowing agent is CFC-141b (1,1-dichloro-1-fluoroethane). With respect to technical feasibility, this material is the nearest competitor to CFC-123 among the substitute CFC blowing agents proposed. The physical properties of

CFC-141b indicate that its performance as a foam blowing agent would be comparable to methylene chloride (68,69).

Compared to CFC-11 or CFC-123, CFC-141b has a relatively stronger solvent affinity for polyurethane polymer, comparable to that of methylene chloride, which dictates that actual production trials would be necessary to verify compatibility between this substitute blowing agent and the various foam products (68). Also, the solvent strength of CFC-141b may preclude its use for producing molded foam parts, as is the case with methylene chloride.

Safety considerations are the major drawback of CFC-141b in foam blowing applications. As discussed previously, flexible foam blowing agents should have low flammability and low toxicity, since their vapors are usually present in detectable concentrations in the plant environment. Toxicological testing on CFC-141b have not been completed; but currently available reports indicate that CFC-141b is a "weak mutagen" (67,69). In addition, CFC-141b is reportedly more flammable than other substitute flexible foam blowing agents (68).

From a technical and safety standpoint, CFC-123 appears to be a good substitute CFC blowing agent for flexible polyurethane foams. The major impediment to its use is cost and availability. These factors are not yet well defined. Recent estimates from DuPont are a bulk price range for CFC-123 of \$2.75 to \$5.50 per kg (\$1.25 to \$2.50 per pound) (69).

In comparison with CFC-123, there is much greater uncertainty associated with CFC-141b application as a substitute blowing agent. Questions regarding in-plant safety hazards and solvent affinity toward the foam product cannot be adequately resolved with presently available information. Despite the apparent disadvantages of CFC-141b, some preliminary development work has been conducted to devise a commercial process for its manufacture. Recent estimates from DuPont are a bulk price range for CFC-141b of \$2.20 to \$4.40 per kg (\$1.00 to \$2.00 per pound) (69).

The potential producer of these substitute blowing agents is confronted with uncertainty. Prior to investment leading to commercialization of a new chemical, the prospective producer must have confidence in market potential. This is especially true in the case of CFC-123 and CFC-141b, for which flexible foam blowing represents a large potential market The problem is that in order to assess the technical feasibility of a substitute CFC as a replacement for CFC-11 (or methylene chloride), commercial quantities must be available for detailed industrial trials. It is not known whether sufficient quantities of either CFC-123 or CFC-141b could be made using existing CFC production facilities.

VOLATILE HYDROCARBON/CFC BLENDS

In addition to auxiliary blowing agents based solely on CFC-11 or methylene chloride, blends of these two compounds, and with other volatile hydrocarbons, may be used as foam blowing agents. Suppliers of blowing agents (e.g., DuPont) currently produce such blended agents. However, their use has not become widespread in the United States.

Presumably, process operation and foam quality would not be adversely affected by use of a blended blowing agent, provided the boiling point and solvent properties are compatible with the particular formulation. One possible concern may be that catalyst packages tailored to either CFC-11 or methylene chloride may not permit proper timing of the polymerization reactions relative to volatilization of the blend. Furthermore, it is likely that the release of blended blowing agent vapor would be spread over a wider temperature range than a single compound. These characteristics could limit the range of formulations that can use blended agents. If blowing agent volatilization is not precisely timed with the development of polymer viscosity, poor cell structure, and incomplete cell opening can result. In extreme cases, foam collapse or splits in the rising bun may occur.

No comparative cost information could be developed for application of blended blowing agents, because reformulation factors and range of usefulness are specific to a particular producer's situation. For this option to be widely used, it is probable that the use of blended agents, on an overall raw material cost basis, must be competitive with currently used systems.

SECTION 7

EQUIPMENT MODIFICATION AND WORK PRACTICES

The potential for reducing CFC-11 blowing agent emissions through modifications in flexible foam manufacturing equipment is somewhat limited by the nature of the flexible polyurethane foam process. The amount of auxiliary blowing agent used and emitted is determined by the chemical formulation for a specified set of foam properties. Also, innovation in foam equipment has generally focused on improved foam products at lower costs, and not reduction of CFC emissions. However, several developments can be cited which permit physical blowing agents to be used more efficiently, thereby reducing the gross quantity consumed for a given foam output.

The conventional arrangement of polyurethane slabstock foam equipment is disadvantageous with respect to minimizing CFC releases for several reasons. First, some of the auxiliary blowing agent is not efficiently used. CFC-11 that flashes before development of polymer liquid viscosity, or that evaporates near the top surface of the horizontal bun, does not contribute fully to expanding the foam. Second, CFC emissions are spread over a large horizontal surface, making collection difficult. Finally, the coincident emissions of TDI over this large area dictates large ventilation flows, resulting in relatively dilute CFC exhaust concentrations and increased recovery costs.

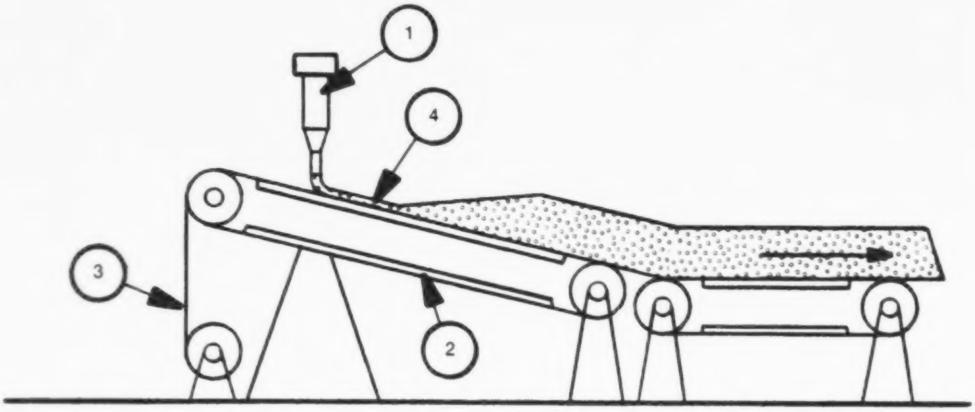
Several alternative foam equipment systems have been developed which reduce the difficulties described above. It is noteworthy that virtually all innovation in this area has occurred in Europe, so that each of the technologies discussed in this section involves royalty arrangements with European equipment firms.

MAX-FOAM® PROCESS (UNIFOAM AG)

This process has become the most popular horizontal foam line configuration, in which a pre-mixed feed stream is introduced at the bottom of a trough, located at the entry to the foam tunnel. Figure 7-1 compares the trough feed arrangement with the older traversing mixer head. As the fed material begins to cream and expand, it overflows onto the moving conveyor web as a uniform mass. The inclination of the initial conveyor section, or "fall plate", is adjustable, so that the rising foam surface can be kept level for various formulations and rise rates. This feature provides the main advantage to foamers. Since the top bun surface does not rise relative to the tunnel walls, the surface tension effects that cause rounding of the bun top are avoided. This results in a flat-topped bunstock that significantly reduces trim waste.

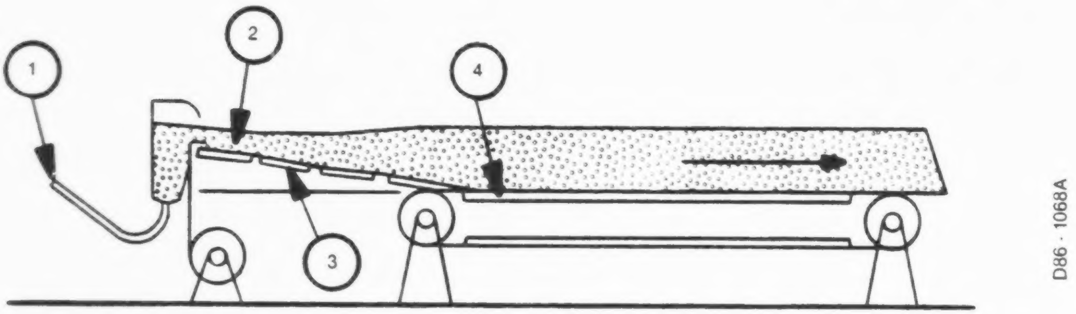
The potential benefit of this process in reducing CFC-11 emissions is a result of the feed trough concept. Since the fresh feed exits the dispensing head at the bottom of a pool of creamy liquid, rather than in the open air, entrainment of the blowing agent is said to be improved. This improves the gas efficiency of physical blowing agents. Also, the flat-topped bunstock reduces trim scrap, so that less CFC-11 is required per unit salable foam output. No data have been published on the actual reduction in CFC-11 use or emissions associated with the Max-Foam® device, but Unifoam AG claims to have confirmed reduction in CFC-11 requirements (10).

Use of the trough-feeding system has expanded in recent years, such that is is now the standard slabstock blowing configuration. One equipment supplier estimated that more than half of all existing slabstock foam installations are of the trough feed type (10). Since the late seventies this type of process has been preferred, primarily because it delivers a flat-top bun having more uniform properties, and this is an important cost benefit for foamers. The success of the Max-Foam® concept has made top paper wrap almost obsolete as a means of controlling bun surface shape. More of the older style



Inclined conveyor/traversing head process.

1 - Traversing mixer head; 2 - Inclined fixed conveyor; 3 - Conveyor lining paper feed; 4 - Deposited foam feed mixture



Max Foam® trough feeding process.

1 - Foam feed line; 2 - Foam overflows pre-expansion trough; 3 - Adjustable inclined fall plate; 4 - Horizontal foam conveyor

Figure 7-1. Comparison of conventional traversing head and trough feeding (Max-Foam®) configurations.

traversing head machines are currently sold to developing countries, and relatively fewer to U.S. firms (10).

Economics are generally favorable for new installations of Max-Foam lines. Capital costs are comparable for both Max-Foam® and older-style traversing head systems. Retrofit of a trough-style dispensing system to an existing conveyor is also feasible. However, the main advantage for Max-Foam® is in material costs; the flat-top bun is of more uniform consistency, so there is less waste. One cost consideration is that purchase of Max-Foam® technology involves royalty payments to the licensee.

VERTIFOAM® PROCESS (HYMAN INTERNATIONAL)

The Vertifoam® process was developed and patented by Hyman International (U.K.), and is a novel approach to production of flexible slabstock foams. The configuration is shown schematically in Figure 7-2. In this process the pre-mixed feed liquid is introduced at the bottom of a totally enclosed vertical expansion chamber. A polyethylene film lining on the inside walls of the chamber draws up the rising foam at a controlled rate. The foam then continues to expand vertically up the chamber, and formed slabs are cut off as they exit the top.

The combined effects of gravity and foam fluid mechanics ensure a stable front as the foam climbs the vertical chamber; the produced foam has a very uniform density and consistency over the entire cross section. Both rectangular and circular foam slabs can be made, having densities in the range of 13 to 48 kg/m^3 (0.8 to 3.0 lb/ft^3) (72).

Vertical chamber height is approximately 5 to 8 meters, and the rate of foam advance is much slower than for horizontal foam lines; 0.6 to 1.2 meters/min (2.5 to 4 feet/min) versus 4 to 5.5 meters/min (14 to 18 feet/min). This results in a total residence time for the foam of about 10 minutes, which is comparable to that in a horizontal foam tunnel (72).

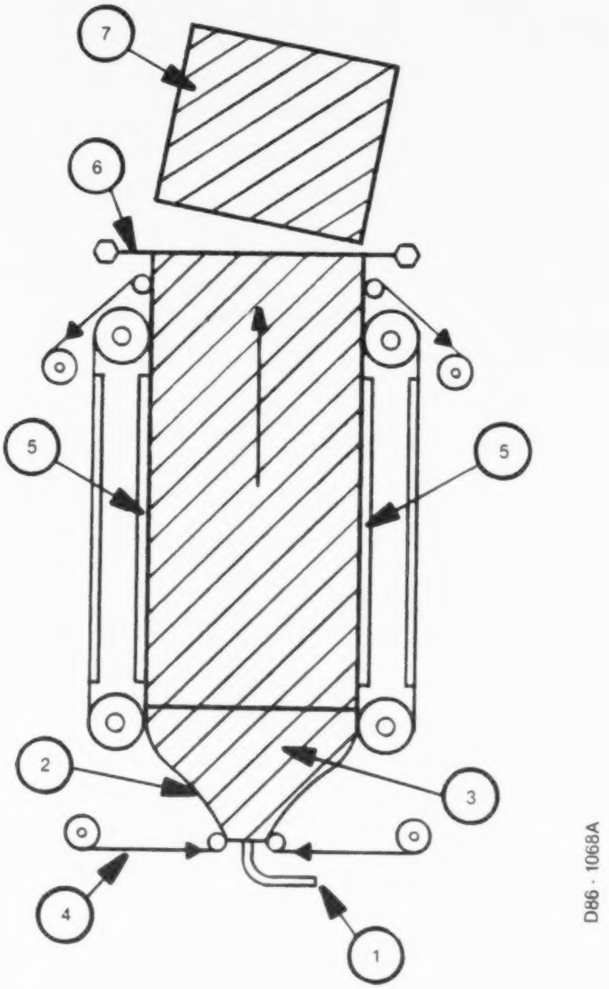


Figure 7-2. Vertical slabstock foam conveyor (Vertifoam®) system.

1 - Foam feed line; 2 - Initial expansion section; 3 - Expanding foam; 4 - Chamber side wall lining film feed; 5 - Side wall conveyors; 6 - Bun cut-off saw; 7 - Completed foam slab

The principal advantage of the Vertifoam® concept in potentially reducing CFC-11 emissions is that these emissions are more confined than for horizontal systems. As in the case of the Max-Foam®, fresh liquid feed enters the foam chamber at the bottom of a liquid pool. Additionally, the evaporated auxiliary blowing agent must diffuse upward through most of the chamber height before being emitted. Both of these factors contribute to improving the gas efficiency of added physical blowing agents. The expanding foam in the Vertifoam® chamber is inherently well-enclosed, and the unit occupies a relatively small floor area, so it is possible that emitted vapors could be more effectively captured and recycled with a much smaller ventilation air flow.

Foam trim waste is reduced by about 15 percent by using the Vertifoam® process, according to its U.S. distributor (10). This means that less total CFC-11 is required per unit of salable foam product. Also, on-line formulation changes, such as in density or coloration, can be performed with a relatively smaller amount of transition waste. However, operation of this foam process can be sensitive to control, since the rise rate of the chamber lining sheets must closely match the rise rate of the foam.

Vertifoam® has been on the market since about 1982. As of mid-1986, four Vertifoam® units have been installed in the United States, and a larger number are in operation in European foam plants (10). Three of the units in this country are owned by Crane Industries, and are located in California, Texas, and Indiana. Future Foam operates a single unit in its Wisconsin plant. Retrofit of an existing foam facility for a Vertifoam® unit appears difficult due to the substantial height of the equipment; about a 15-meter (50 ft.) vertical clearance is necessary (8). Foam conveying systems need to be remodeled when Vertifoam® equipment is used.

Since vertical foam chamber units are mechanically and structurally more complex than horizontal foam systems, capital costs for equipment are expected to be somewhat higher. The U.S. distributor estimates equipment capital expenses to be about a factor of two higher than for conventional trough-feed systems. However, the vertical foam chamber unit occupies considerably less floor space (about 90 m^2) than horizontal lines (typically 600 m^2), so total plant capital expenses should be nearly equal. Overall raw material savings on a per unit salable foam basis are claimed to be between 4 and 11 percent, due to reduction in foam waste (72). Labor and warehousing costs are claimed to be reduced in Vertifoam® plants because of slower production rate.

VACUUM MOLDED FLEXIBLE FOAM (BAYER AG)

A proposed alternative to the use of CFC-11 in molded foams is "vacuum blowing" technology. This concept involves foam formation under less than atmospheric pressure, and has been demonstrated by Bayer AG of West Germany (11).

By reducing the air pressure within the mold, low foam density is possible without auxiliary blowing agents. This is because the same amount of primary CO_2 blowing agent will occupy a larger volume, and provide greater foam porosity. For example, a reduction in mold pressure from 760 mm Hg to 500 mm Hg (about 34 percent of atmospheric pressure) is stated to produce a foam with density equal to a formulation containing 15 weight percent CFC-11 (11).

Practical application of vacuum molding is difficult, mainly because mold vent design is complex. Bleeding of expanding foam through large vents increases the portion of reject parts. But large area vent ports are necessary to maintain a uniform vacuum throughout the mold, and to ensure uniform foam density. Bayer AG has tested a redesigned automatic vacuum vent which promises to correct this problem.

No economic or specific operating data have yet been published on this relatively new process.

WORK PRACTICES IN FLEXIBLE FOAM PLANTS

In polyurethane flexible foam manufacturing, auxiliary blowing agent emissions can not be greatly reduced by changes in work practices alone. The gas emission rate associated with production of a given foam grade depends on the quantity of physical blowing agent required to achieve specified density and softness properties. Relatively little CFC-11 is emitted from a foam plant that is not charged as part of the foam formulation. However, two simple control practices that could reduce emissions can be implemented.

Work practices that could reduce total CFC-11 emissions include overall improvement in plant maintenance, and detection and repair of fugitive leak sources. Potential sources for leakage emissions include pumps, pipe fittings and flanges, pressure relief devices, sampling and delivery connections, storage tanks, and open dispensing lines. To date, no field study has addressed this source of CFC-11 losses from flexible foam plants. However, a recent survey of flexible foam producers using methylene chloride has shown that fugitive sources can account for about two percent of total blowing agent losses from these facilities (5). It is anticipated that a similar proportion of CFC-11 emissions would arise from fugitive sources.

This same survey estimated that routine leak detection and repair would reduce these fugitive emissions by about 60 to 75 percent. More extensive measures, such as replacement of pressure relief valves with rupture disks and installation of caps on delivery lines, would completely eliminate releases from some fugitive sources. It was also found in the recent study of methylene chloride emissions that leak detection and repair may only be marginally cost effective, in terms of cost per unit emissions averted. Curtailment of emissions from fugitive equipment leakage was estimated to cost \$3,000 to \$13,000 per metric ton controlled, and from storage tanks \$64,000 to \$153,000 per metric ton controlled (73).

SECTION 8

ALTERNATIVE CHEMICALS AND PROCESSES

In recent years, there have been significant developments in the area of alternative chemicals and processes as a means of reducing or eliminating CFC-11 emissions from flexible foam plants. All the systems reported to date retain the basic framework of polyol/isocyanate reactions to generate the polyurethane polymer. Each differs in the specific polyol and/or isocyanate compounds used, and in some cases new ingredients are introduced to the formulating scheme. Usually, the overall goal of these new formulations is to improve foam performance or production, but secondary objectives include increasing the effectiveness of the primary blowing agent (i.e., CO_2), and thus reduce the need for auxiliary blowing agents. However, in some cases there are limitations on the range of foam density and/or firmness properties.

WATER-BLOWN HR MOLDED FOAMS

The HR (high-resilience) concept for molded foam products is essentially a specific approach to formulation. There are few substantive differences in mechanical operation between this newer process and the older hot molded process. The most significant is that the HR formulations do not require an oven to provide curing heat. Both processes are described in detail in Section 4 of this report.

Currently, HR process technology, with or without CFC-11 blowing agent, is widely used in production of automotive and furniture cushioning components. Its advantages have made the older hot molded technique nearly obsolete. As of 1980, about 82 percent of automotive flexible foams produced in the United States were made via the HR process; by 1983 this fraction had grown to over 90 percent (11). In Western Europe, HR foams account for about 45 percent of all automotive flexible foam components.

Suppliers of polyurethane feedstock chemicals have reported that it is possible to produce virtually all currently used molded foam grades without CFC-11 blowing agent. As described below, polyurethane systems are now available, based on either MDI (methylene diphenyl isocyanate) or TDI reagents, that promise to greately reduce or eliminate CFC-11 use.

Process Chemistry

Water-blown, flexible molded HR foams are based on families of polyols having enhanced reactivity. MDI or TDI can be utilized as the isocyanate reagent, and there are advantages and limitations associated with either type of system. Also, the use of carefully balanced catalyst blends and surfactants has been noted to be a key to obtaining consistent, high quality foam (74,75).

In general, MDI-based polyurethanes undergo more abrupt viscosity build-up and polymer gelation. This characteristic limits the dispersion of the open cells within the foam, so the range of densities possible without an auxiliary blowing agent is limited. It has been stated that MDI systems can produce automotive molded foams as low as 32 kg/m^3 (2.0 $lb./ft^3$), and non-automotive (e.g., furniture) foams in the 43 kg/m^3 (2.7 $lb./ft^3$) range. Typically, MDI-based foams that do not use CFC-11 will have densities of about 48 kg/m^3 (3.0 $lb./ft^3$) or higher (39). Because of their more rapid gelation, MDI-based foams require more auxiliary blowing agent to achieve lower density than TDI-based systems. One benefit of MDI is that it is less likely to evaporate into the plant environment, because its vapor pressure is lower than for TDI.

Because MDI reagents contain fewer reactive isocyanate groups per unit weight, greater amounts of these compounds are required per unit foam. While water-blown HR systems generally have higher raw material cost, suppliers state that there are offsetting advantages in productivity. Because of its more rapid gelation, MDI foams have shorter demold times than older CFC-blown systems, and total curing times are also reduced (11). Newer TDI-based HR systems also offer shorter demold times.

The physical properties of MDI-based HR foams are attributed to the formation of suspended solid polymer particles which increase polymer strength. Chemically, this is a result of the larger and more rigid molecular structure of MDI (i.e., two phenyl groups). For higher density foams, this characteristic offers an expanded range of load-bearing properties without modifying foam density (39,43). Because the foam cell walls have greater strength, mechanical crushing of demolded MDI-based foams is necessary to promote cell rupture and improve softness.

HR molded formulations based on TDI have expanded the applicability of water-blown systems to components requiring lower density and high softness, such as auto seat backs. In the reactions that form polyurethane foam, water contributes to the formation of urea linkages between polymer chains. Currently available TDI systems take advantage of these urea linkages to build polymer strength, without cross-linking additives often required for CFC-blown systems. Blended polyol feedstocks can be specified to achieve the desired load-bearing properties; and foam densities as low as 24 kg/m^3 (1.5 lb./ft^3) can be achieved. An additional ingredient, diethanolamine (DEOA), may also be included (about 1 - 2 parts per hundred polyol) to assist in viscosity development. Combinations of amine and tin catalysts are tailored for a specific fomulation (74).

Control Applicability and Status

The increased application of water-blown HR molded foams based on either MDI or TDI appears to be a promising technique of reducing CFC-11 emissions. Given current U.S. auto seating specifications, widespread use of TDI-based systems would be favored for large-volume high-softness components such as seat backs. However, for higher density components, or cushioning for which improved load-bearing capacity is desirable, MDI systems may be favored. The availability of both types of HR formulations allows individual producers to maintain product versatility, satisfy consumer preferences, and reduce CFC-11 use. Overall, the current auto industry trend is toward systems utilizing little or no CFC-11, due to the cost and processing advantages of newer water-blown systems.

Extremely low molded foam densities, that is, approaching 16 kg/m^3 (1.0 lb./ft^3), are not readily achieveable with water-blowing. However, the use of denser, higher-resilience foams is expected to increase as autos become smaller. In general, as the loaded to unloaded weight ratio of an automobile becomes greater, the suspension must be more tightly sprung; therefore, ride comfort depends on the cushioning properties of the seats. Also, increased durability would favor a reversal of the current trend to lower density foams in furniture uses (19).

For the most part, MDI-based water-blown systems for automotive and furniture components are practically limited to the higher density grades. These foam systems were first commercialized by ICI in West Germany in 1979, and since that time have gained a minor market share. This is due, in part, to differences in consumer preferences between the European and U.S. markets. In Europe, auto seats having greater density and more firm feel are prefered, and MDI formulations are well-suited to these grades. As of 1983, 11 percent of automotive molded foam produced in Western Europe utilized MDI-based polyurethanes (11). Systems using MDI are commercially availiable in the United States, but market penetration is relatively small.

One apparent drawback of the MDI-based molded foams is that reduction in foam density to match that obtained with TDI-based formulations requires substantially higher portions of CFC-11 blowing agent. Development work is continuing to enable MDI-based foam technology reach current U.S. auto density and firmness specifications without CFC-11 (39). However, given the current status water-blown MDI foams are limited to higher-density applications, such as auto interior moldings.

Water-blown HR systems based on TDI remain the more versatile technology; such systems are currently available for virtually all large-volume molded foam grades. Major producers of molded foams, especially auto manufacturers, have been investigating the use of solely water-blown systems, and have begun to phase out CFC-11 blowing. Difficulties still remain in application of water-blown HR foam for lowest density components. These include collapse of the foam in the mold, unacceptably high reject rate, and need for labor-intensive repair of imperfect parts (15).

Development Potential and Economics

From the foam industry perspective, the increased application of water-blown molded foam systems will permit continued reductions in the use of CFC-11. This is especially true in the automotive industry. The use of water-blown systems is compatible with increased foam densities, and higher density is normally associated with greater durability.

Raw material costs for water-blown TDI foams are nearly equivalent to conventional systems using CFC-11 blowing agent. Although a more expensive polyol or combination of polyols is generally needed, this cost is offset by the omission of the auxiliary blowing agent, and cross-linking additives. For this reason, differential raw material costs for the water-blown TDI systems do not exceed one percent of the costs of conventional CFC-blown systems (74).

In the case of MDI-based polyurethane foams, raw material costs for the water-blown formulations generally exceed those of conventional CFC-blown systems by about 5 percent (39). This is mostly due to the increased amount of the MDI reagent required to obtain an equivalent isocyanate reactivity. The omission of the CFC-11 blowing agent does contribute to offsetting this additional cost. Since MDI-based foams tend to have greater load-bearing strength, the need for additives to increase cross-linking is also reduced.

There are some retooling and redesign costs associated with the conversion to totally water-blown molded HR foam, for either TDI or MDI systems. These costs are highly dependent upon the application; automotive firms state that these costs are significant (15,34,76), while for other end-use industries retooling costs may be negligible. With regard to fabrication labor and other operating costs, the major conversion expense is associated with part rejection and repair rate. At this time, the portion of demolded parts needing repair can be high when water-blown TDI systems are used for low-density auto components. But future development is expected to improve this situation. For most density grades, TDI-based molded foams can be produced with less than one percent reject rate. MDI foam systems are equally reliable, based on European production experience in which part reject rates can also be below one percent (43). However, these foams are limited in the range of density and softness possible.

In a performance-oriented market, such as in molded flexible foam, slight increases in cost can be justified in creating a higher quality end product. In addition, the costs for molded foam constitute a tiny fraction of total production costs for an automobile. These factors would appear to favor increased application of water-blown HR foam in the future, even in the absence of CFC-11 emission regulation.

WATER-BLOWN SLABSTOCK FOAM TECHNOLOGIES WITH MODIFIED POLYURETHANE CHEMISTRY

Solely water-blown slabstock polyurethane foams produced using conventional reagents generally have restricted cushioning properties. This quality has been attributed to the greater formation of urea linkages within the polymer structure, causing the cell walls to be more rigid. Therefore, use of water as the sole blowing agent has generally been restricted to high firmness foams. Innovations in foam chemistry reported in recent years could modify this view, and reduce the need for auxiliary blowing agents over a wider range of foam grades. New chemical systems that could expand the versatility of slabstock technology while reducing the need for auziliary blowing agents have received some attention. The two examples discussed below involve changes in the characteristic polyols and isocyanates used and inclusion of new ingredients in the foam formulation.

Process Chemistry

One possible technique to achieve improved foam softness without auxiliary blowing agent is the use of so-called "soft" polyols. This class of materials consist of polyol resins having fewer cross-linking sites per unit weight, which reduces the natural rigidity of the polymer chains. Other reports in this area indicate that "soft" polyols typically have a higher molecular weight than currently used compounds (37). This would result in greater spacing of cross links along the polymer chain. Polyol functionality, that is, the number of hydroxyl (-OH) end-groups, in conjunction with the polyol molecular weight are indicative of the polyols inherent reactivity and final polymer structure and rigidity.

In 1983, researchers at Union Carbide described a polyurethane foam chemical system that could produce foams in the 24 to 40 kg/m^3 (1.5 to 2.6 lb/ft^3) range, with firmness characteristics comparable to conventional foams in the 25 to 40 ILD range (76). These formulations represented a new approach, based on established technology. The developers cited two differences compared to conventional chemical systems. One was the use of higher molecular weight blended polymer polyols (e.g. polyoxypropylene-polyoxyethylene with polyacrilonitrile-polystyrene co-polymer), and the addition of diethanolamine (DEOA) to the foam formulation.

In this modified polyurethane system, higher molecular weight polymer polyols possessing higher reactivity hydroxyl sites lead to longer polyurethane chains. The inherently higher activity of the proprietary polyol helps balance the concurrent foam gelation and blowing (i.e. CO_2 liberating) reactions. Inclusion of 0.85 to 1.3 parts of DEOA per hundred polyol builds improved froth viscosity and stability by reacting with some of the TDI reagent. Developers claim it is possible to vary the foam hardness by changing the amount of DEOA used, in formulations containing from 2.1 to 3.75 parts water per hundred polyol, without using auxiliary blowing agents. Union Carbide also stated that developments in catalyst formulation could widen the range of achievable foam properties.

Also in 1983, Montepolimeri S.p.A. of Italy reported the development of a new polyol/isocyanate system which was claimed could produce high softness foams with densities as low as 21 kg/m^3 (1.3 lb/ft^3) (77,78). This chemical system was also said to deliver high density, high softness foams that could not be made with conventional technology.

The specific structure of the polyol was not revealed, but it was reported that polymeric isocyanates are used along with a patented polymeric polyol having molecular weight of about 3000. Details concerning the type of compounds used were not disclosed. However, the foam formulations and process chemistry are similar to that for conventional polyurethanes. Typical foam formulations would contain 2 to 4.8 parts water per hundred polyol, and specifically-designed catalyst blends are necessary to achieve desired foam properties.

Control Applicability and Status

Modified polyurethane foam systems are potentially applicable to essentially all existing polyurethane slabstock foam manufacturing processes. According to developers, most of the common firmness grades are attainable with these systems. Control of CFC-11 emissions would be 100 percent for these products, if the modified chemistry would permit the auxiliary blowing agent to be omitted from the feed material. New advances in this area may even extend the practical range of foam properties. For example, the Italian system promises to extend the range of slabstock properties to include high density, high softness foams. But this system cannot deliver the low density slabstock currently made through the use of auxiliary blowing agents.

It is possible that all water-blown polyol/isocyanate systems such as these will offer product quality equal or better to that achieved with conventional chemistry. The resilience characteristics of some of these foams are judged to be better than some presently used materials in certain end-uses.

In recent years, formulations based on HR technology have become available for slabstock production. These systems still employ CFC-11. However, as in the case of molded foam, these formulations could lead to reductions in CFC requirements without loss of foam versatility (37). Currently, water-blown slabstock, with conventional or HR formulations is still restricted to higher densities (i.e., greater than about 48 kg/m^3 (3.0 lb/ft^3).

At present, the development of modified polyol systems remains at the laboratory investigation stage. High firmness grades are presently produced with conventional chemical systems, but the volume demand for these products is small (see Figure 3-1). A minor niche for soft, water-blown foams does currently exist in the United States market in low volume, specialty foams such as sterilized medical packaging (79). To significantly affect CFC-11 emissions, newly developed systems should be aimed at large volume slabstock grades, to allow replacement of a substantial percentage of conventional CFC-11 blown foam products.

Development Potential and Economics

Given present slabstock market economics, the potential for expanded use of alternative polyurethane foam chemical systems is limited, even with the impetus of restrictions on CFC-11 use. Although the modified slabstock technologies offer some cost savings by eliminating most or all of current CFC-11 use, these are generally higher chemical costs. Furthermore, there is still some penalty in the ability to achieve low-density foam products. However, preliminary development work continues, and the outlook for market acceptance may improve in the future.

Inertia within the foam industry, as well as currently higher costs for these new chemical systems are barriers to near term implementation of this method of controlling CFC-11 emissions. Before modified polyol systems would be commercialized, there would need to be additional development to make costs and versatility of these systems competitive. For the new chemical systems to be accepted on a large scale, foam producers would have to gain a certain degree of experience and confidence in their use.

Factors which favor implementation of this control are that relatively little capital investment is necessary, and that several aspects of product quality are better with the new systems. In particular, foam resiliency and softness delivered by these newer water-blown formulations is claimed to be better than water-blown foams based on conventional systems. The risk of fire or scorching of the foam is greatly reduced with the proposed isocyanates, since internal foam temperatures are not as high as conventional water-blown polyurethane foam. Also, these new foam products have improved flame retardancy characteristics.

FORMIC ACID PROCESS (INNOCHEM, S.A., SWITZERLAND)

Another proprietary chemical system that has been recently invented incorporates formic acid instead of auxiliary blowing agents to produce low-density flexible foam (80,81). This new system was developed by Kabel-und-Gummiwerke AG in Belgium, and is licensed by Innochem, SA in Switzerland. In this process, termed the "AB" process (for Alternative Blowing), formic acid replaces water in the formulation, and reacts with isocyanate to liberate the foam blowing gas. The developers state that this chemical scheme was not discovered earlier because organic acids neutralize conventional amine catalysts. For this reason, a specially-developed amine catalyst configuration is part of this new technology.

Process Chemistry

A key difference between the AB foam process and conventional foam chemistry is the reaction of formic acid with isocyanate to both liberate blowing gas, and form urea linkages in the polymer. In these reactions, double the amount of gas is released as with water/isocyanate, making an auxiliary blowing agent unnecessary. However, the additional gas is carbon monoxide (CO) which is recognized as a toxic gas having a time-weighted average (TWA) exposure limit of 50 ppmv (82). Also, vapors from the concentrated formic acid reagent are a strong respiratory irritant with a TLV of 5 ppm (83). This means that careful monitoring of the plant air is crucial when the formic acid process is used.

The developers of the AB foam process state that since TDI emissions currently dictate high plant ventilation rates, the emitted CO should not escape from the foam line enclosure (81). However, a European evaluation of this technology reported that CO emissions in foam storage areas would be significant, so that increased ventilation would probably be necessary (50).

Other chemical features of the AB/formic acid process include a more narrow processing range that must be maintained with respect to tin catalyst. This dictates more careful process control to insure product quality. Another is that a proprietary amine catalyst which is not neutralized by formic acid must be included in the formulation. The AB foam process requires somewhat less silicone surfactant than in conventional systems, to avoid excessively fine cells.

Control Applicability and Status

This AB/formic acid process was licensed in 1983, but no commercial-scale demonstration has been reported since that time. According to the developers, it is applicable to the production of most flexible slabstock and molded foam grades (80). However, further evaluations have indicated some limitations on applicability, especially for molded foam (50). Because of concern about the safety of this process, near-term commercial development does not appear favorable. Ventilation needs for CO and formic acid vapors must be considered, and handling precautions are essential for concentrated formic acid.

Development Potential and Economics

Since auxiliary blowing agents are not required for the AB/formic acid process, this technology would completely eliminate CFC-11 emissions over an appropriate range of foam grades. There are some technical and safety issues questions to consider before widespread implementation can be endorsed. For instance, the release of carbon monoxide could prove to be a serious drawback in commercial production.

An advantage of this technology, compared to other process modification methods, is that there are relatively fewer limitations on the achievable range of foam properties. This would minimize dislocations in the various end-use markets for polyurethane slabstock, especially since production costs for this new process are competitive with conventional systems.

It is claimed that capital expenditure needed to convert to the AB chemical system is minimal. In 1983, Innochem SA stated that equipment costs for the conversion would be between \$5,000 and \$10,000 for typical slabstock plants (80). These costs would cover minor changes in feed pumping equipment, and installation of carbon monoxide monitoring devices. However, it is likely that these equipment costs underestimate overall conversion expenditures, since additional ventilation, and retooling with acid-resistant materials are not considered. On balance, raw material savings could be substantial; each kilogram of formic acid is said to replace about four kilograms of CFC-11 formerly required. But, royalty payments to the licensee will absorb about one-third of the projected savings (80).

In the absence of commercial scale operating data, it is not possible to verify the economic impacts associated with this process. Overall, it appears that the cost of foam products could decrease with this new process. Although equipment costs and range of applicability have not yet been thoroughly assessed, if the technical and safety questions can be favorably resolved, then commercial demonstrations of the AB process might be forthcoming.

SECTION 9

SUBSTITUTES FOR FLEXIBLE FOAM PRODUCTS

Because of the low cost and versatility of polyurethane flexible foams, little development effort has been aimed at new substitute materials. Given the mature position of the foam industry and consumer expectations, it is not probable that end-use markets would voluntarily revert to older cushioning technologies, such as cotton batting and coil springs. Also, the effect of foam price on the most end products is relatively inelastic; so even large increases in foam costs would not result in proportional reductions in demand. However, substitute materials can be proposed for nearly all end uses, even if they do not have the ideal properties of polyurethane foam.

DEVELOPMENT POTENTIAL FOR ALTERNATE MATERIALS

A number of cushioning products are adaptable to current polyurethane foam uses. Some examples are:

- Cotton or polyester batting and coil springs;
- Rubberized horsehair with support frame and springs;
- Natural and synthetic fiberfill;
- Latex and rubber foams;
- Corrugated soft plastic or semi-flexible foam structures;
- Solid plastic contour seating with natural fiber cushions; and

- Engineered firm foam structures with internal voids.

All of these possibilities drastically reduce, or eliminate, the role of soft, low-density foams that require auxiliary blowing agents. The above list includes outdated technologies, and more recently developed ideas, some of which are currently used only in novelty consumer goods. It does serve to point out that it is physically possible to recreate the cushioning performance of flexible polyurethane with many alternate products.

Before any alternative to polyurethane foam is adopted for widespread applications, it is important to consider secondary effects. As presently used, polyurethane foam is a very high-volume product. As discussed in Section 3 of this report, consumption of these flexible foam materials currently exceeds 650 thousand metric tons per year (1,470 million lbs/yr). Should any alternative product displace a large portion of this consumption level, secondary environmental, economic, and energy effects must be considered.

Over the long term, it is possible that new cushioning materials, including new types of flexible foam, could be developed and marketed. At present, there is little incentive to pursue this. It is certain that the development effort, and evaluation of the possible secondary effects, would take more than a few years. For this reason, it is impossible to predict or evaluate the associated costs for such longer-term means of reducing CFC-11 emissions.

Economic Factors

The natural evolution of cushioning products in the free market has resulted in the dominance of flexible polyurethane foam. Numerous economic reasons can be cited for this; but in essence, it is accepted that these foam materials best satisfy consumer preferences at lowest production cost. Virtually all presently available alternative products are at a great disadvantage in this regard.

Still, there are a number of materials that are competitive, or nearly competitive with flexible polyurethane foam. Packaging and rug underlay market segments are two examples. Rug underlay materials such as corrugated foam rubber, natural and synthetic fiberfill, jute, and latex foam are now, or have been competitive with polyurethane foam. Numerous packaging materials are available at comparable costs, so that relatively minor aesthetic preferences or availability considerations are sometimes the main factors in selecting polyurethane foam packaging.

Secondary economic factors associated with conversion to alternate materials are also important. These factors include losses in sales and jobs due to increased end-product prices; increased energy and raw material resource consumption, and possible loss in competitiveness of end-use products in foreign markets. The increased consumption of petrochemicals and fuel reserves would result from large volume uses of heavier plastic structures in cushioning. If metal-supported, natural fiber seating were adopted in automobiles, there would be penalties in fuel economy and competiveness with imported autos, due to increased vehicle weight.

Product safety is another important area in which polyurethane foam holds an advantage. This material is more easily made fire retardant than older materials. Also, polyurethane foams are non-toxic and less susceptible to mildew and dry rot than most other cushioning types. It should be pointed out that latex foam, which was a predecessor of polyurethane foam in many uses, can equal flexible slabstock foam in these areas, but its density and cost are considerably higher (84).

The most probable role for currently available substitute cushioning materials is in end uses for which the characteristics of polyurethane foam do not deliver an essential benefit. Some conversion to currently available alternate materials would be expected if the price of polyurethane foams increased. Certain packaging and furniture applications could be converted to alternate materials with little penalty in performance or cost. For example, natural or synthetic fiberfill is currently used interchangeably with low-density polyurethane foam for some furniture products. However, barring a large increase in foam prices, substitutions of this kind would be expected to displace only a small portion of current flexible foam use. Development of innovative cushioning systems might occur in those markets which had sufficient revenue and adequate research support (e.g., automobiles) to commercialize new materials.

At present, it appears that there are three general types of substitute for flexible slabstock foams that could gain a significant market share:

- Natural/synthetic fiberfill;
- Alternate Foams and built-up cushioning systems; and
- Innovative engineering materials based on porous plastics technology.

It is anticipated that these materials could replace a moderate fraction of slabstock or molded foam consumption in response to regulatory pressures. The first two alternatives represent currently available technology, and some materials in these categories are presently competitive with slabstock foam.

Barriers to Implementation

At present, most potential alternative products would be considerably more costly to produce in volume comparable to polyurethane foam demand. Not only are materials costs equal or higher than for polyurethane, but many alternatives, such as built-up cushioning systems, are more labor intensive to produce. The prospect of considerable capital expenditure in flexible foam end-use industries is also an obstacle to acceptance of non-foam materials. No data is available to quantitatively estimate the economic impact of these factors.

Another barrier often cited is the need to remain competitive with foreign-made products which use polyurethane foam. In the absence of worldwide cooperation, American products would be at a disadvantage if competing with consumer goods for which flexible foam is standard, such as furniture and automobiles. Overall product acceptance could suffer as well, it is mainly the comfort and cost advantages of polyurethane foam that has led to its wide use.

Large development and capital expenditures would be necessary to commercialize materials with the sophisticated properties that can now be engineered into flexible foam. Such properties as flame-retardance, a wide range of firmness grades, light weight, and durability, cannot be matched by any currently feasible alternative. It is not clear that equivalent properties are even possible for alternative materials in all applications. Equivalent substitutes, even if less convenient, do not presently exist for most polyurethane foam uses.

Development of entirely new cushioning technologies may be possible, but should be considered a long-term possibility. Engineered materials based on porous plastics or semi-flexible foam may be envisioned as potential replacement materials. But, such products would have yet to be developed, and commercialization expenditure would be large.

SPECIFICATION OF MINIMUM DENSITY FOR FLEXIBLE FOAMS

One possible modification in current flexible foam products that could reduce CFC-11 emissions is to establish a minimum density for foams used in different end uses. Since auxiliary blowing agents are used to reduce foam density, as well as to enhance the softness, the quantity of CFC-11 used per unit foam increases as foam density decreases. But, in general it is possible to achieve an acceptable range of foam softness at higher densities with substantially less auxiliary blowing agent.

Economic Factors

As foam density increases, greater amounts of expensive polyols and isocyanates are required per unit volume of foam. However, the resulting higher-density product is usually of higher quality and will last longer (19,37). Consumer education and labeling on increased-density foam products should promote acceptance, provided the price increases are reasonable.

Foam producers generally respond to the demands of their regional clientele regarding the quantities and densities of foam produced. In addition, the competitive nature of the flexible foam industry generally requires that producers minimize product cost in order to survive. This generally favors production of lower density foams. From the foam manufacturing viewpoint, it is preferable to purchase more auxiliary blowing agent, instead of costly polymer reagents. These conditions have led to the widespread adoption of low density foam for many products, especially furniture, that could be of higher quality and durability if made with higher density foam.

It is estimated that establishment of a minimum flexible foam density could cut CFC-11 emission by 20 to 50 percent. This could be accomplished without modification to existing foam plant equipment, and thus represents a viable short-term control option.

From the standpoint of the foam producer, the immediate direct cost is in larger quantities of raw materials per unit volume of foam. These added materials costs increase proportionately to the increase in product density. To illustrate, if a given board foot output is shifted from 16 to 22.4 kg/m^3 (1.0 to 1.4 lb/ft^3) then raw material costs would increase about 40 percent.

It would also be necessary for higher density foams to be accepted by the manufacturers of products using flexible foam. If this were to occur, the foam producers would not have difficulty complying with a mandated minimum density specification. However, the customers of slabstock and molded foam producers are generally under competitive price pressures, as dictated by the consumer marketplace. Thus, a minimum density foam standard might effect reductions in CFC-11 use not only by replacement of low-density foam by higher density, but also by causing an overall reduction in total foam demand.

Although not developed in this study, a detailed market analysis to define the economic impact of this control measure would be a necessary first step for implementation. The effect on consumer prices for certain end-use products, such as furniture and automobiles, would be expected to increase only slightly, since foam material cost accounts for only a small fraction of the total manufacturing cost. A greater effect would be felt in the foam market itself; shifts in both production distributions, and price structure, would be expected to occur.

Specification of an optimal minimum density for individual end uses should be based on a technical evaluation of the essential properties for that use. For example, greater durability resulting from increased foam density is advantageous in furniture; higher-priced furnishings already use more dense foam than items aimed at the low-price market (19). In contrast, higher densities may be detrimental in packaging or portable cushioning products, for which low weight is a priority.

Barriers to Implementation

There are relatively few technical barriers to adoption of increased flexible foam densities. Nearly all slabstock and molded foam producers have the capability to manufacture a range of densities. In many cases, this property is set by the relative portions of water and auxiliary blowing agent in the feed formulation. This means that no significant operational changes are needed, and existing foam formulations can continue to be used. It is possible that some facilities will incur some equipment modification cost in shifting to a higher-density product line.

Economic and subjective barriers pose a greater obstacle to acceptance of higher density flexible foams. Elimination of low-density materials will affect the product distribution of some producers more than others. Also, producers tend to match their product specifications to suit customer demands. Therefore, the foam industry may have to convince some of its clients to use heavier, possibly costlier foam products. It is anticipated that specification of reasonable minimum densities for the individual end-use markets could ease acceptance. From the foam producer's viewpoint, unless there is some assurance that higher raw material costs can be passed to customers, without loss of competitiveness, foam output may decline.

Lack of detailed market information poses another practical barrier to implementation of higher density foams. It is important that foam consumption be characterized as a function of density and firmness, to provide a basis for establishing minimum density standards. Foam production data at this level of detail is not available.

SECTION 10

SUMMARY OF TECHNOLOGICAL CONTROL OPTIONS FOR CFC-11 IN FLEXIBLE FOAM MANUFACTURE

In the production of flexible polyurethane foams, CFC-11 is used as a physical blowing agent to reduce foam density and increase softness. Inclusion of an auxiliary blowing agent increases the volume of gas liberated within the polymer matrix during foam rise, and therefore, increases the total cell volume. CFC-11 is used in this manner for both flexible slabstock and molded foam, and the portion of blowing agent in a given formulation depends on the density and softness specifications of the product.

In 1985, it is estimated that 11.5 and 3.3 thousand metric tons (25.3 and 7.3 million pounds) of CFC-11 were used in the production of slabstock and molded foam, respectively, in the United States (2). Emissions of CFC-11 blowing agent from flexible foams are prompt, that is, the gas is released during, or soon after, foam formation. Therefore, the quantity of CFC-11 emitted essentially equals the consumption.

This study has evaluated several technical options with the goal of reducing the emission of CFC-11 from flexible foam plants. A number of candidate control technologies have been examined with respect to engineering, safety, and economic factors. The availability and current status of these technologies were also evaluated. When possible, detailed engineering and cost analyses were presented to determine the cost effectiveness of control. Also, relevant barriers to implementation for each control method have been identified, and where possible, a time frame was suggested for control implementation.

This section serves to summarize the salient points presented in this report by comparing several of the control technologies. In addition, areas are identified in which more detailed technical and/or economic studies are needed.

COMPARISON OF AVAILABLE TECHNICAL OPTIONS

The techniques for control examined in this study include add-on controls (such as carbon adsorption), substitute blowing agents, alternative flexible foam processes, and substitute products. Comparisons among these options can be broken down into technical and economic factors, development potential, and relative control cost effectiveness.

Short-Term Control Alternatives

The CFC-11 emission control options viewed as possibilities for short-term implementation in flexible foam manufacturing facilities are:

- Substitution of methylene chloride blowing agent;
- Establishment of a standard minimum foam density;
- Application of lower density substitute materials (e.g., natural/synthetic fiberfill);
- Process leak detection and repair; and
- More widespread use of water-blown HR molded foam formulations.

The factors given the most weight in selection of appropriate short-term measures were the magnitude of emission reduction potentially achievable, control costs, and availability of the necessary technology. It was also considered important to minimize the impact of short-term controls on the existing foam industry structure. Since there is relatively little new plant construction within the foam industry, it is anticipated that the most effective control measures must be implemented at existing foam facilities.

The first listed option, substitution of methylene chloride blowing agent for CFC-11, is presently applied to a great extent to produce flexible foam slabstock. Although methylene chloride has a higher boiling point than CFC-11, advances in the past ten years in catalyst chemistry have facilitated increased conversion from CFC-11. The availability of methylene chloride conversion as a control measure is excellent. It is estimated that as much as 75 percent of all flexible slabstock foam could be produced using this alternative blowing agent without degrading foam quality. But given present technology, it is not possible to use methylene chloride to a significant extent in producing molded foam parts. There are two main concerns with increased application of methylene chloride as a foam blowing agent: (1) possible toxic effects on plant workers and (2) the inability to produce as diverse a range of foam properties as with CFC-11. Because the toxicity issue is a concern and an uncertainty, careful precautions and continuing study are advisable.

Another control approach which would effectively reduce CFC-11 use and emissions in the flexible foam industry would be to establish a minimum allowable density for flexible foam products. Since auxiliary blowing agents are needed mainly to reduce foam density, this policy would effectively reduce the amount of CFC-11 (or methylene chloride) that would be used, perhaps by as much as 50 percent. An important advantage of this policy, compared to methylene chloride substitution alone, is that it could apply to both flexible slabstock and molded foams. Another positive factor is that emission reductions could be realized without development of new technology or substantial capital expenditure.

A careful market analysis would be required to define the overall economic effects of a minimum foam density standard. One key factor would be the final foam product cost since producers would be expected to pass higher foam chemical costs on to consumers. Total demand for flexible foam may decline due to unavailability of low density grades. Or, the use of higher density foam may adversely affect the competitiveness of end products. It should be possible to determine both the cost per unit emission averted and the total quantity of emission controlled as functions of specific values of minimum foam density.

It has become accepted that flexible polyurethane foam materials best satisfy consumer expectations and preferences at lowest overall product cost. However, some conversion to other available materials would be expected as a result of increased price and/or reduced local availability of polyurethane. For example, natural and/or synthetic fiberfill materials (e.g., polyester batting) are now used interchangeably with polyurethane foam for the outer layers of furniture cushioning, and mattress upholstery backing. Net differences in material costs are small in these cases, and the major relative costs of the product substitute are in the product fabrication step.

Many of the economic considerations relating to product substitutes are similar to those described in connection with a minimum foam density specification. If the use of substitute materials were required, then there could be a loss of competitiveness, because consumers may prefer products which contain flexible foam. In addition, consumer prices for end-products would probably increase if substitute materials involving higher production costs were used.

As an additional control measure, leak detection and repair programs can be applied. These programs are applicable to all flexible foam producing facilities and would utilize readily available maintenance practices. But, while this measure rates high on availability, the potential emission reductions are small. For this reason the cost effectiveness of this control measure is poor, with expenditures of 3 to 150 thousand dollars per metric ton of emissions controlled (73).

Another relatively short-term control option would be more widespread application of water-blown HR molded foam formulations based on either TDI or MDI reagents. There is already substantial penetration of this technology, especially among major producers, and it is possible that CFC-11 use in molded foam production can be completely eliminated by using these formulations. Certain technical problems remain, but progress is this area is encouraging.

Longer-Term Control Alternatives

Consideration of longer-term CFC-11 emission control measures expands the scope of options to include developmental technologies, and those with larger or less predictable impacts on the foam industry. This study has identified several longer-term control approaches:

- Carbon adsorption with CFC-11 recovery;
- Newer, less ozone-depleting CFC blowing agents;
- Water-blown slabstock using modified polyol chemistry; and
- The formic acid, or "AB" slabstock process.

The most important criteria used to evaluate longer-term measures were a high level of emission curtailment, and long-term technical feasibility. Less emphasis was placed on the immediate availability of each technology and on the impact of these controls on the existing foam industry. These factors can not be reliably predicted, because these controls require extensive technical development prior to large scale commercial implementation.

At present, carbon adsorption is by far the most fully developed of the long-term control technologies. Carbon adsorption and recovery of CFC-11 has been shown, in two separate pilot studies, to be possible in flexible foam slabstock plants. While this technique generally involves increased plant operating costs, there is a potential credit for reclaimed blowing agent. Overall CFC-11 recovery efficiencies as high as 40 percent have been demonstrated in pilot tests (42), and it is postulated that efficiencies up to 70 percent are possible with ventilation modifications to full-scale foam lines

(13). It is felt that carbon adsorption is more applicable to flexible slabstock lines than molded foam plants, since higher CFC-11 concentrations exist in typical foam tunnels, compared to open molded foam carousels. And, the slabstock process can be more readily enclosed to restrict the exhaust volume.

High capital costs are the single greatest barrier to implementation of carbon adsorption controls. Any technical improvement or economic incentive that could reduce capital expenditure, or increase recovery credit, will greatly improve the potential applicability of carbon adsorption/recovery systems. For example, improved recovery efficiency and/or an increase in CFC-11 market price dramatically enhances cost effectiveness.

Other problems with carbon adsorption in flexible foam applications include the deactivation of the carbon by TDI and/or amine catalyst residues. It is known that these chemicals will be retained in the adsorber bed, and react with regeneration steam to form residues that are not removed by steam regeneration. Ultimately, the carbon surface becomes deactivated and CFC-11 removal efficiency can decrease (42,47). Methods to overcome this problem, such as the sacrificial carbon guard bed concept proposed in this study, have not been tested. Secondary pollution effects from large-scale use of carbon adsorption must also be considered. Usually there is a large volume steam condensate stream, which must be treated and recycled, or disposed. Also, issues regarding disposal or regeneration of fouled carbon have not been investigated to date.

In comparison with carbon adsorption, there is relatively little information currently available to permit evaluation of other possible longer-term control options. There is considerable uncertainty regarding the commercial potential of developmental slabstock foam chemical systems using modified polyols that could eliminate the need for auxiliary blowing agents. In the case of alternate CFC blowing agents, commercialization has been slowed by the lack of an assured market and technical obstacles in developing an economic production process. At this time, the developmental details for both modified polyol systems and alternate chemicals are held as proprietary. While such controls presently rate rather low in availability, their effectiveness in reducing eliminating CFC-11 use could be very high. Developments have been reported in this area which are applicable to both flexible slabstock and molded foam production.

One promising long-term control measure for CFC-11 emissions is substitution of newer, less-ozone-depleting CFC foam blowing agents. There are three possible candidate compounds which have physical properties suitable for flexible foam blowing: CFC-123, CFC-133a, and CFC-141b. These are examples of hydrogen-containing chlorofluorocarbons which are theorized to be less stable in the atmosphere than CFC-11. As a result of this reduced stability, these alternative blowing agent molecules would tend to be broken down prior to reaching the upper atmosphere, and thus would contribute much less to stratospheric ozone depletion.

Of the currently proposed newer, alternative CFCs, use of CFC-123 appears to be safe and technically feasible. Limited testing has been successfully conducted with CFC-123 on a commercial slabstock foam line. But development of a commercial production process has been hindered by technical problems and the lack of an assured market for CFC-123. CFC-133a has been found to be embryotoxic, and its boiling point is too low for practical use as an auxiliary blowing agent. CFC-141b is a slightly flammable compound, and conclusive toxicity testing has not been completed.

In comparison with add-on engineering emission control measures, reductions in the use of methylene chloride blowing agent through modifications in polyurethane foam chemistry offers somewhat more promise. Several suppliers of foam chemicals are reportedly researching new polyurethane systems that could produce a range of slabstock grades while reducing or eliminating the use of auxiliary blowing agents. The current status of this research is at the fundamental laboratory level, and more development is needed before commercial potential can be assessed (84).

In 1983, new polyurethane chemical systems for production of flexible slabstock were introduced by Union Carbide and by Montepolimeri S.p.A. of Italy, respectively. Each of these systems employ modified polyols or polyol blends to create a foam with enhanced resilience and softness properties without the use of auxiliary blowing agent. As in the case of carbon adsorption controls, the chemical systems described above can be applied directly in existing flexible foam plants. Unlike add-on adsorption/recovery control processes, the modified chemical systems require little, if any, capital expenditure.

Another new slabstock process has been developed in Belgium and involves the use of formic acid to replace some of the water in the foam formulation. The reaction between formic acid and isocyanate releases twice the volume of gas as the water/isocyanate reaction, so sufficient blowing action is obtained to produce low-density foam without an auxiliary blowing agent. One drawback of this process is that the gas liberated by the formic acid reaction is carbon monoxide, a recognized toxic gas with a time weighted TLV of 50 ppmv (82). This necessitates special precautions in plant ventilation and air monitoring. Handling the concentrated formic acid reagent will also require special ventilation and construction materials. The process claimed to be applicable to production of a range of density and firmness grades of foam; but the equipment and plant ventilation modifications required to apply the new chemical system may be costly.

Less Promising Control Alternatives

The remaining CFC-11 emission control techniques evaluated in this study were generally considered to be less technically or economically feasible. These include:

- Exhaust incineration, either thermal or catalytic;

- Liquid absorption with recovery;

- Direct vapor condensation;
- Solely water-blown foam using conventional polyurethane chemistry; and
- Use of higher-density alternate foams and built-up cushioning systems.

These technologies presently appear to be poorer candidates as control measures for CFC-11 emissions from flexible foam plants. This assessment is based on a preponderance of negative technical and economic factors associated with these options. In particular, extremely high capital and operating costs are encumbered with the add-on control methods in the above list. All of the listed control options would have negative secondary effects, such as increased consumption of energy and natural resources, that can not be accurately predicted.

Substitution of higher-density alternative cushioning materials may be favored for certain end uses, but the potential market penetration of this control is uncertain. Materials such as latex foam could be used interchangeably with flexible foam in some end uses, but with substantially higher cost. New engineered materials may become available if price or availability limit consumption of flexible polyurethane foam, but no significant effort has been made in this area.

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